Coordination and Multi-Objective Optimization Framework for Managing Municipal Infrastructure Under Performance-Based Contracts

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ABSTRACT

Coordination and Multi-Objective Optimization Framework for Managing Municipal Infrastructure Under Performance-Based Contracts

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One-third of Canada's municipal infrastructure is in fair, poor and failing condition states. Aging infrastructure systems are placing tremendous pressure on governments through steeply growing budget deficits and an urgent need for replacement. Municipalities are experiencing high inefficiency and financial burden imposed by their under-performing infrastructure, which in return increases the risk of service disruption and leaves decision-makers with no choice but undertake immediate interventions. The estimate of Canada's infrastructure deficit is ranging between $110 billion to $270 billion. The massive number of infrastructure intervention activities occurring in cities leads to detrimental social, environmental, and economic impacts on the community. Thus, coordinating the interventions of the co-located assets (i.e. roads, water, and sewer) is progressively becoming of importance to cope with those tough challenges. It will decrease the number of service disruptions and reduce the rehabilitation costs by integrating the joint activities shared among the co-located assets. Numerous attempts have been made by previous scholars to enhance the infrastructure performance within the limited budgets. Yet, most of their efforts were geared towards short-term intervention planning for a single asset, without accounting for the potential coordination savings (i.e. cost, disruption time, consumed space, amount of service disruption, and end users' inconvenience).

In the lights of those issues, this research proposes a coordination and multi-objective optimization framework for managing the municipal infrastructure under performance-based contracts. The framework proposes an integrated contractual and asset management solution to aid decision-makers in both the pre-contract and post-contract phases. In the pre-contract phase, the system will find a near-optimal set of key performance indicators thresholds' as well as their associated penalties and incentives that meet the end users' expectations without having an escalated contingency at the contractual price. In the post-contract phase, it will provide a near-optimum coordinated interventions' schedule/plan for the municipal infrastructure. To

build the framework, the research went through three main phases: (1) literature review that thoroughly studied and analyzed the municipal contractual practices, optimization, and integrated asset management; (2) contractual scheme, coordination, and multi-objective optimization asset management system where a novel contractual scheme was introduced and a coordination and optimization-based asset management system was developed; and (3) system integration and model implementation where the contractual scheme was integrated with the coordination and optimization-based asset management system to aid decision-makers in taking informed pre-contract and post-contract decisions. The coordination and optimization systems were built to quantify and evaluate the potential savings of coordinating the maintenance, whether partially or fully, as opposed to the conventional approach. It revolves through three core models: (1) central database that contains detailed asset inventory for the infrastructure systems, (2) multi-dimensional performance assessment computational models that assess the potential coordination savings for the three coordination scenarios based on eight indicators (time, space, cost, risk, resilience preparedness, condition, efficiency, and effectiveness); and (3) two multi-objective optimization models: (a) multi-objective hierarchical goal optimization that relies on a set of meta-heuristic rules and genetic algorithms optimization engine; (b) multi-objective linear programming optimization that reaches an exact solution using MOSEK software.

To demonstrate the system's functionality, it was applied to the roads', water and sewer networks of two case studies namely: (1) city of Montreal; and (2) town of Kindersley. Both displayed huge savings in favor of the coordinated approach as opposed to the conventional one. For the city of Montreal, the system was developed on sophisticated spreadsheets combined with a genetic algorithms'-based optimization engine (Evolver) and was applied to both pre-contract and post-contract phases. The pre-contract optimization was able to obtain a near-optimal set of key performance indicators' thresholds and their associated penalties and incentives. The post-contract optimization displayed an overall improvement of 15% across 25 years planning horizon as a result of coordinating the interventions as opposed to the conventional scenario. The 15% improvement was broken down to 12%, 16%, 18%, 30%, 26%, 10%, 10% for the time, space, cost, efficiency, effectiveness, condition, and risk respectively. For the town of Kindersley, the system was developed on REMSOFT software integrated with MOSEK optimization engine. The results displayed an overall improvement of 29% across 25 years planning horizon because of coordinating the interventions as opposed to conventional ones. The 29% improvement was broken down to 72%, 63%, 48%, 67%, 9%, 1%, 14%, and 5% for the time, space, cost, efficiency, effectiveness, condition, resilience

preparedness and risk respectively. Furthermore, the coordinated intervention program resulted in 67% fewer interventions as opposed to the conventional approach, saving an overall of 374 interventions across the 25 years, equivalent to 15 interventions annually, which drastically reduces the public disruption. In conclusion, this research proposes an integrated coordination, optimization, and contractual solution for the municipalities and maintenance contractors to enhance their expenditures' utilization, minimize the service disruptions, and improve their assets' performance under tough budgetary constraints.

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Finally, the long journey is over. I am fortunate that I had an opportunity to choose this route. I am glad I made it through and again, thanks to everyone who have touched my life.

DEDICATION

"*Success or failure is an own decision*"

This thesis is dedicated to all my family and friends all over the worlds. This work is intended to be nothing but a step towards attaining a better future for us in our daily lives. This thesis is equally the least dedication I can offer to my beloved wife **Meriem Rguib**, who has been supportive since I started my journey. I dedicate this thesis to my parents, **Amr Abusamra** and **Ghada Saad**, who provided invaluable support to me during the course of studies and gave me an extreme momentum to exert all my efforts towards success. In addition, I offer this thesis to my young brother, **Ehab Amr** and my cousin and best friend, **Omar Abusamra**. Furthermore, I dedicate this thesis to the soul of my great grandfathers, **Soliman Abusamra**, the minister of irrigation, and **Saad El-Sherif,** who passed away a few months ago. I really wished he was alive to experience that day, but life is too short. Rest in Peace grandfather, you will be always in my heart.

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NOMENCLATURE

CHAPTER 1 - INTRODUCTION	GDP: Gross Domestic Product	CHAPTER 3 - RESEARCH METHODOLOGY	AADT: Average Annual Daily Traffic
	LOS: Level of Service		SDC: Standalone Direct Costs
	PBC: Performance-based Contracts		SIC: Standalone Indirect Costs
	KPIs: Key Performance Indicators		JDC: Joint Direct Costs
	P/I: Penalties/Incentives		JIC: Joint Indirect Costs
CHAPTER 2 - LITERATURE REVIEW	PAS: Publicly Available Specification		LIF: Life-Cycle Costs Improvement Factor
	ISO: International Standards Organization		DT: Disruption Time
	GIS: Geographic Information System		IDT: Inter-Disruption Time
	ANP: Analytic Network Process		TDT: Total Disruption Time
	LCC: Life-cycle costs		IEF: Intervention Efficiency Factor
	CP: Compromise programming		OT: Operating Time
	GAs: Genetic Algorithms		IFF: Intervention Effectiveness Factor
	POF: Probability of Failure		CCS: Corridor Condition State
	COF: Consequences of Failure		C or R: Condition or Reliability
	SFL: Shuffled Frog Leap		CIF: Condition Improvement Factor
	MAUT: Multi-Attribute Utility Theory		F: Demand-Capacity Ratio
	GAMS: General Algebraic Modeling System		GCMs': General Circulation Models
	CPLEX: C programming-based solver using Simplex method		GPA: Grade Point Average
	SFL: Shuffled Frog Leap		RIF: Risk Improvement Factor
	FANP: Fuzzy ANP		CHI: Corridor Health Index
	ANN: Artificial Neural Network		NHI: Network Health Index
	PPP: Public-Private Partnership		BOQs': Bill of Quantities
	SMART: Specific, Measurable, Achievable, Realistic, and Timely to schedule		S_{var}: COF scoring range
	SoS: Systems-of-System		DW: Decomposed Weight
	HLA: High-Level Architecture		PVC: Poly Vinyl Chloride
	RI: Risk Index		CT: Clay Tavern
CHAPTER 3 - RESEARCH METHODOLOGY	SD: Standalone Duration		VC: Vitrified Clay
	PD: Parallel Duration		AC: Asbestos Cement
	JD: Joint Duration		CS: Corrugated Steel
	ASD: Asset Standalone Duration		STL: Steel
	CCD: Corridor Coordinated Duration		DI: Ductile Iron
	NCR: Network Coordination Ratio		CI: Cast Iron
	A: Area		RC: Reinforced Concrete
	STDF: Spatio-Temporal Disruption Factor		GALV: Galvanized Steel
	STIF: Spatio-Temporal Improvement Factor		CIP: Pitted Cast Iron
	I: Rainfall Intensity		CIS: Spun Cast Iron
	A: Sub-catchment Area		CU: Copper
	RCM: Regional Climate Models		CP: Concrete Pressure
	IDF: Intensity-Duration-Frequency		HDPE: High-Density Poly Ethylene
	RPIF: Resilience Preparedness Improvement Factor		DIHY: Ductile Iron Hyprotech
	CRPS: Corridor Resiliency Preparedness State		IRI: International Roughness Index

1 CHAPTER 1 - INTRODUCTION

This chapter starts with an overview of asset management along with several challenges facing municipalities while maintaining their assets. Hence after, it discusses the problem statement and describes the major triggers for each problem. Thenceforth, the research objectives are pinpointed. Finally, the thesis structure is pointed out for easier follow-up.

1.1 Background

Infrastructure is the foundation of our daily lives. The strength of this foundation enables our communities to prosper and local businesses to grow. Infrastructure development is a vital component that encourages the country's economic growth. Finance Canada report has recently shown that $1 billion investment in infrastructure creates 16,700 jobs and boosts the Gross Domestic Product (GDP) by $1.6 billion (CCPA 2009; MGI 2017; Abu-Samra 2016a; 2016b). Developing the infrastructure enhances the country's productivity, consequently making firms more competitive, and boosts the region's economy. Not only does the infrastructure enhance the efficiency of production, transportation, and communication, but it also plays a pivotal role in providing economic incentives to public and private sector participants. The accessibility and quality of infrastructure in a region help in shaping domestic firms' investment decisions and determine the region's attractiveness to foreign investors. Proper management of these vast systems is necessary to ensure that our communities continue to prosper. Infrastructure asset management is defined as "*the systematic, coordinated planning and programming of investments or expenditures, design, construction, maintenance, operation, and in-service evaluation of physical facilities*" (Haas *et al.* 1994; Hudson *et al.* 1997). It covers all the activities that guarantee a minimal acceptable infrastructure Level of Service (LOS) to be brought up to the public. These activities range from the initial information acquisition that is required for calculating the public need for a specific type of infrastructure, to the maintenance and rehabilitation needed to maintain a proper LOS, from the infrastructure preliminary design and construction to the monitoring and evaluation process. Infrastructure asset management is not just about managing an existing facility to deliver an intended service, but it is also about taking critical decisions for properly investing the limited government resources to both; meet the need for building new infrastructure and keep the existing infrastructure within an acceptable LOS. Deferred investments for the existing infrastructure systems in many countries led to an extreme decline in the systems' LOS, the need for costly replacement, and in some cases sudden catastrophic failures.

Even though infrastructure is deemed to be the foundation of the city to develop, Canada's aging municipal infrastructure is placing tremendous pressure on the government through steeply growing deficits to repair/replace the failing assets. The deficit was estimated at \$123 billion for existing infrastructure, growing by \$2 billion annually, and \$115 billion for constructing new infrastructure to satisfy the growing population, which has doubled in 40 years from 17.9 million in 1960 to 35.1 million in 2013 and is expected to be 42.5 million by 2056 (Mirza 2007; 2009; Brodhead *et al.* 2014; Statistics Canada 2017). Recent studies estimated Canada's infrastructure deficit at a range between \$110 billion to \$270 billion (Berz *et al.* 2017; BCG 2017). Furthermore, urbanization represents another challenge for asset managers. According to the United Nation Population, the world is undergoing the largest wave of urban growth. In 2008, more than 50% of the world's population was living in towns and cities and the figures are expected to exponentially swell throughout the upcoming years (UNFPA 2007; Moir *et al.* 2014; Michaelson *et al.* 2008). Moreover, increased density of residential developments substantially increases the number of impervious surfaces from which rainfall runs-off quickly into the pipe system (Mailhot and Duchense 2010). According to Environment Canada, the urbanization of natural drainage basins can increase water runoff to more than 400% (Water security agency 2014). Precipitation trends from recent decades showed an increased frequency of extreme rain events in many regions and climate change is suspected to be the direct cause (Madsen *et al.* 2009). Furthermore, the Intergovernmental Panel on Climate Change (IPCC) estimated a temperature increase of 1˚C to 3.5˚C by the year 2100, due to the increase in greenhouse gases (Houghton *et al.* 1996; Warrick *et al.* 1995). Furthermore, IPCC claimed that there is a 90% chance of augmented heavy rainfall events' frequency in the 21st century and a probable increase in higher-latitude storms by 40%, as a consequence of global warming, which is expected to continue. Warmer temperatures will, most likely, strengthen the hydrological cycle, resulting in an increase of precipitations' intensity and the number of storm events. Meanwhile, the growth of the urban population has been accompanied by an increase of impermeable surfaces and consequently urban runoff volumes, aggravating flooding events (IPCC 2007).

Although there is a clear need to better manage the existing municipal infrastructure, only a few municipalities have a coordinated asset management plan for their road, water, and sewer systems (InfraGuide 2006). While many municipalities have implemented pavement management systems, most do not have asset management plans for their water and sewer systems (De Leeuw 2015; Kesik 2015). Typically, these systems have longer service lives as opposed to the roads, but their condition is usually not visible and needs complicated technologies to be assessed. Several cities have developed and documented asset management plans to better utilize their expenditures (Cambridge 2013; Edmonton 2012; 2014; Essex 2014; Ontario 2012; Hamilton 2013; Gordon 2012; Shah *et al.* 2004). However, those plans failed to consider the interdependency among the systems. InfraGuide (2003a) outlined an integrated approach for the assessment and evaluation of municipal road, water, and sewer networks. The approach consists of five steps: (a) data inventories, (b) investigations, (c) condition assessment, (d) performance evaluation, and (e) renewal plan. InfraGuide (2006) outlined the need for coordinated renewal planning of municipal road, sewer, and water systems at a network level. It emphasized the same five-step procedures mentioned in InfraGuide (2003a) for assessing and evaluating the municipal infrastructure. Furthermore, it mentioned that the asset management planning framework should include clear policy objectives and established priorities. Elaborating on these perspectives reveals more integration aspects such as; top-down decision-making approach, where goals, objectives, and policies are the main decision-making drivers; and bottom-up management approaches, where the technical conditions of different assets and the daily intervention aspects are the main decision-making drivers. Furthermore, integrating the decision-making across multiple levels (i.e. municipal, city, province, and federal) have not been thoroughly investigated yet.

1.2 Problem Statement

Municipalities are experiencing high inefficiency and financial burden imposed by their under-performing infrastructure. One-third of Canada's municipal infrastructure is in fair, poor and failing condition states (FCM 2016). Consequently, the risk of sudden failures and service disruptions drastically increases, which forces taking immediate corrective actions for maintaining the infrastructure assets. Moreover, aging worldwide infrastructure systems are placing tremendous pressure on governments through steeply growing budget deficits and an urgent need for replacement. Therefore, it is obvious that there is an urgent need for adopting innovative and effective asset management approach that minimizes the expenditures without scarifying the minimum LOS threshold. Infrastructure projects typically carry out tons of challenges and risks throughout their life-cycle due to demand fluctuations, uncertainties, natural disasters occurrence, necessity, and criticality, etc. In such type of projects, crucial intervention decisions are, not only taken at the early beginning of the life-cycle but regularly revised to guarantee the delivery of an acceptable LOS while meeting the tight budgets and upholding with the minimal physical condition constraint. Thus, various alternatives need to be considered to best utilize the available expenditures and resources while meeting the tight budgets. The need for asset management adoption has been strengthened by several infrastructure problems (i.e. sudden system failures), as well as the deteriorating LOS, which in return placed tremendous pressure on the governments as they need to increase the expenditures to enhance the infrastructure LOS. Urbanization represents another challenge besides the aging infrastructure systems. According to the United Nation Population, more than 50% of the world's population was living in towns and cities in 2008 and the figures are expected to exponentially swell throughout the upcoming years (UNFPA 2007). This, in return, increases the demand on the existing infrastructure (i.e. more traffic on roads, more processed water, larger sewer pipes, etc.) and forces asset managers to consider resiliency while taking the rehabilitation/replacement decisions (i.e. expand the road and build extra lane, larger water and sewer pipes, build another water pumping station, sewer treatment plant, and water reservoir, etc.).

1.3 Research Objectives

The goal of this research is developing a coordination and optimization asset management framework under Performance-based Contracts (PBC). The framework will aid decision-makers in both the pre-contract and post-contract phases. The pre-contract phase will provide decision-makers with an optimal set of Key Performance Indicators (KPIs) thresholds as well as their associated Penalties/Incentives (P/I). The post-contract phase will provide a near-optimum coordinated interventions' schedule/plan for the municipal infrastructure. To reach this goal, the research should achieve the following objectives:

1. Develop an integrated PBC contractual scheme and identify and study the criteria for selecting the KPIs of each infrastructure.
2. Design a multi-dimensional performance assessment model.
3. Determine the optimized KPIs' thresholds and their associated P/I system.
4. Establish an optimized coordinated intervention plan.
5. Build a PBC-based asset management system.

1.4 Research Methodology

A comprehensive research methodology is detailed in chapter 3. However, this section aims at briefly summarizing the key stages, as shown in Figure **1.1**:

1. *Literature review and criteria identification stage:*

The first stage in the research is conducting an exhaustive literature review on various areas such as; optimization, municipal contractual practices, and asset management. The outcome of this stage will be a precise identification of the municipal common practices, integration parameters, KPIs, and optimization techniques.

2. *Contractual scheme and multi-dimensional performance assessment models' development:*

The second stage in the research is the development of an integrated PBC contractual scheme that opts at involving the private sector in the coordinated intervention for the right-of-way infrastructure. Hence after, the contractual scheme will be validated by applying it to a case study and verifying the results. Furthermore, this stage aims at developing multi-dimensional assessment models that evaluate the remunerations of coordinating the systems' interventions as opposed to the conventional intervention, where the systems' interventions are separately planned and implemented for each asset.

3. *Asset management system implementation and validation:*

The final stage in the research is the system implementation, where the decision-making system is applied to two case studies for results' validation. The outcome of this stage will be either recommendation for the KPIs' thresholds and P/I system in case the system was used in the pre-contract mode, or intervention action plan, in case the system was used in the post-contract mode.

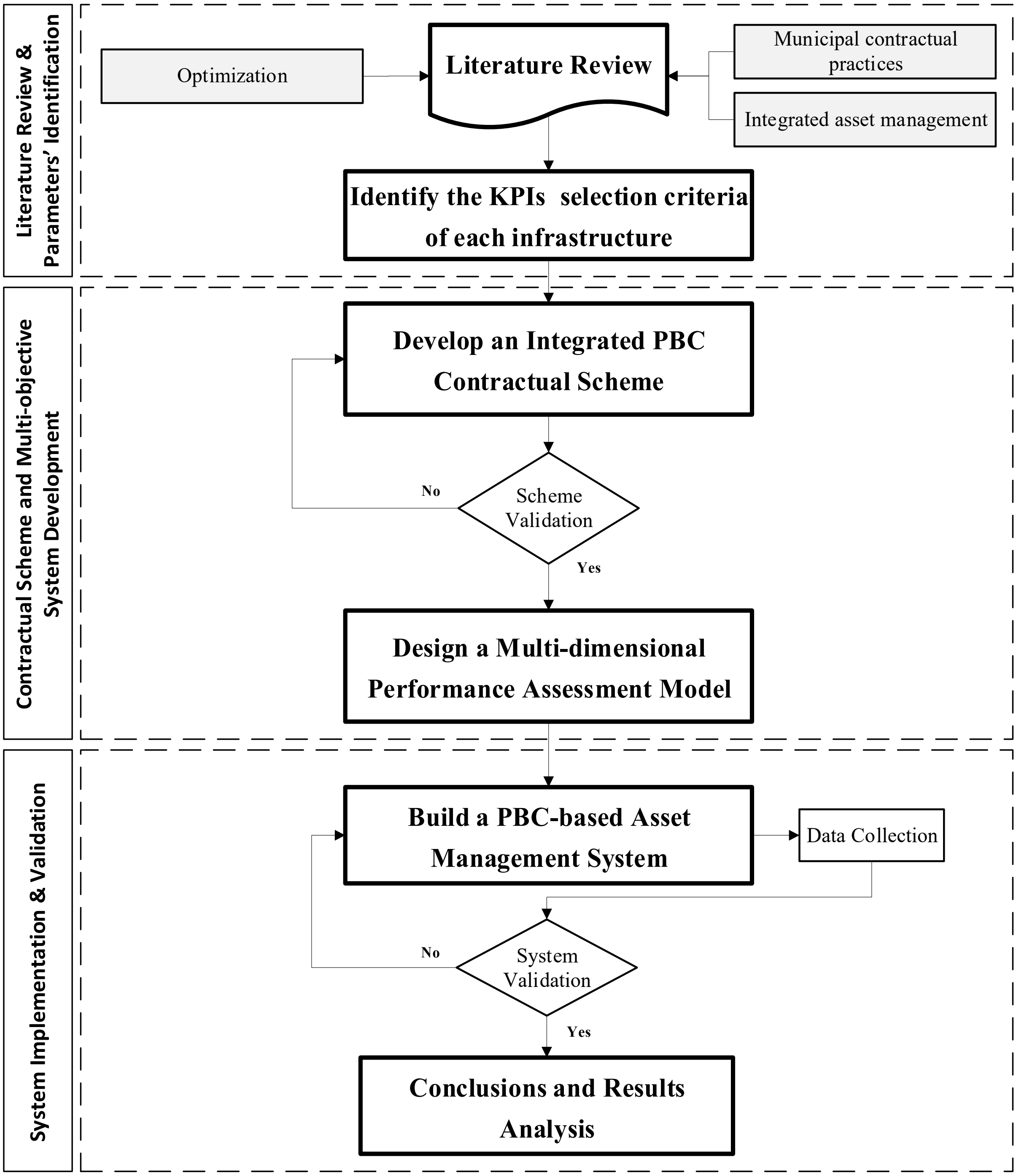


Figure 1.1: *Schematic research methodology*

1.5 Thesis Structure

The thesis is divided into six chapters as follows:

Chapter 1 – Introduction: It starts with asset management overview along with the municipal challenges. Then, the problem statement is pinpointed, where numerical figures are provided to highlight the problem triggers. Hence after, the research objectives are stated. Finally, the thesis structure is pointed out for easier follow-up.

Chapter 2 – Literature review: It provides a state-of-the-art review for the optimization, municipal contractual practices, and asset management. Each section will be thoroughly reviewed and discussed. Findings and limitations will be analyzed, and research gaps will be identified.

Chapter 3 – Research Methodology: It explains the main research methodology and discusses the mathematical formulation of each model. It comprises three main sections: (1) contractual scheme, (2) multi-dimensional performance assessment models, and (3) optimization models.

Chapter 4 – Data Collection and Processing: It displays the raw data and data processing prior to implementation. The data collection was split into two sections for the two case studies: (1) city of Montreal; and (2) Town of Kindersley. The data within each category is further discussed and analyzed.

Chapter 5 – Results and Analysis: It discusses the application of the research methodology to the two case studies. Thenceforth, the results and outcomes of the pre-contract and post-contract optimization models are discussed and analyzed. Hence after, a sensitivity analysis is carried out to study the impact of changing the reliability threshold on the other KPIs and the model is validated.

Chapter 6 – Conclusions and Future Directions: It summarizes the research and its' findings, Thenceforth, it outlines the key contributions to the body of knowledge. Hence after, it states the main limitations and provides future directions for enhancing and expanding the research in the subject matter. Following this chapter, the bibliography and appendices are attached.

2 CHAPTER 2 – LITERATURE REVIEW

This chapter aims at providing a comprehensive literature review on areas related to the research objectives. Those areas fall under those three broad categories: optimization; municipal contractual practices; and integrated asset management. It discusses various single and multi-objective optimization techniques in the asset management domain. Hence after, it studies the current municipal contractual practices to spotlight the downsides of those practices and overcome them in the newly-developed contractual scheme. Finally, it reviews the state-of-the-art work in the integrated asset management.

2.1 Chapter Structure

The chapter starts with a brief overview of the problem in hand. Then, the literature review takes place in three main areas, as shown in Figure 2.1. The 1st area is the optimization in the asset management domain, which is necessary given the complexity of the problem in hand. In this area, single and multi-objective optimization techniques, algorithms, and decision-making systems will be investigated. The outcome of this area is selecting a proper optimization technique and algorithm that fits the novel multi-objective optimization technique. The 2nd area is the municipal contractual practices, where conventional maintenance and rehabilitation contracts, as well as PBC, will be thoroughly studied along with their KPIs and associated P/I systems. The outcomes of this area are: (1) a concrete understanding of the current municipal contractual practices along with the areas that can be potentially improved to facilitate the implementation of the novel contractual framework; and (2) definition of the contractual KPIs, their thresholds and associated P/I for building an integrated PBC asset management system. The 3rd and final area is the integrated asset management, where state-of-the-art articles will be reviewed to investigate the selected dimensions, indicators, interdependency, weights of importance, coordination savings, and socio-economic effects. The outcome of this area is a solid understanding for the potential coordination savings as well as the indicators used for modeling the problem in hand.

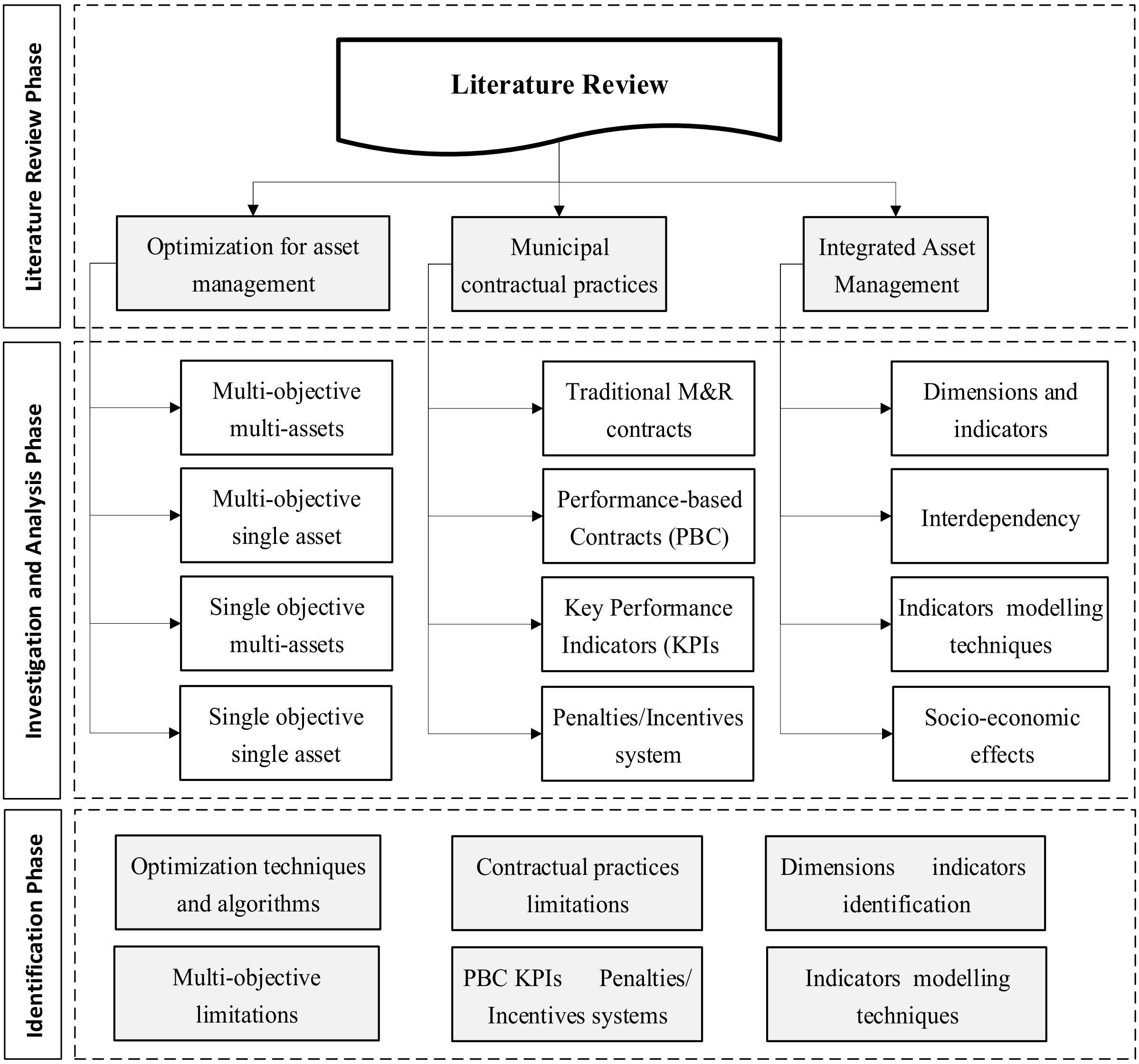


Figure 2.1: *Literature review hierarchical flowchart*

2.2 Overview

Enhancing life-cycle planning and fund allocation is increasingly becoming more vital to municipalities and utility operators to cope with the increasing challenges. Municipalities are financially overloaded due to the substantial increase in the under-performing and deteriorating assets; and the lack of enough funds to pay the increasing infrastructure deficit debt (Mirza 2007; 2009; Uddin *et al.* 2013; FCM 2016). According to the 2016 World Economic Forum survey, Canada's infrastructure quality is ranked as "Mediocre" with a significant portion of assets in poor and very poor condition states. Moreover, between 30% and 50% of Canadian infrastructure assets will soon require attention or replacement, which increases the risk of municipal services' disruption. Furthermore, the estimated replacement value of the assets in very poor, poor and fair condition states for the roads, water, wastewater, and stormwater is $296.5 billion (Berz *et al.* 2017; BCG 2017; Abu-Samra 2017c). Similarly, US infrastructure needs $4.6 trillion to restore it back to an acceptable level. The gap between required and available budgets between 2016 and 2015 alone exceeds $2 trillion, for which governmental investments need to increase from 2.5% to 3.5% of US GDP by 2025. Moreover, an extra $206 billion are required annually to avoid increasing the gap consequences on the US economy (ASCE 2017).

Besides aging and deterioration of municipal assets, Canadian municipalities are facing other challenges that could be summarized as follows: (1) infrastructure deficit is estimated at $273 billion and is growing by $2 billion annually (Mirza 2007; 2009); (2) growing population and urbanization (i.e. the population increased from 17.9 million in 1960 to 36.7 million in 2017 and is expected to reach between 40.0 and 63.5 million people by 2063 (Statistics Canada 2017); (3) increasing demands on higher levels of services by taxpayers; and (4) low share of taxes, compared to provincial and federal governments, and huge responsibility for the largest share of public assets.

From an economic perspective, the estimate of Canada's infrastructure deficit is ranging between $110 billion to $270 billion. Based on the estimated needs, the deficit is estimated to reach $200-300-billion by 2025 (Berz *et al.* 2017; BCG 2017). The infrastructure deficit is manifested as a lack in the annual investment rate. For instance, even though the targeted investment rate is between 1% to 1.5% to maintain drinking water supply systems in an acceptable condition state, the actual annual investment rate of drinking water pipes is about 0.9%. Similarly, the linear wastewater needs an investment rate between 1% to 1.3% and the actual rate is 0.7%. Likewise, the roads and sidewalks need investment rate between 2% to 3% and the actual rate is 1.1%, and so on for all the municipal assets. Based on current investment levels, the condition state of the road, water, and sewer assets are anticipated to further decline. The total value of the core municipal infrastructure assets in Canada is estimated at $1.1 trillion dollars in which municipalities own and maintain nearly 60% of and get only 8% of the taxes (FCM 2016). Similarly, the estimated global infrastructure deficit in the US is about $1 US trillion and $65 US trillion investments are required by 2030 (ASCE 2017). Some scholars argued that adopting proven best practices could increase the productivity of infrastructure investment. For instance, a 4% savings could save an average of $1 trillion a year in infrastructure costs through 2030 (MGI 2013; 2017).

Under the current financial challenges, the coordinated planning of the co-located municipal infrastructure networks such as; roads, water, and sewer could offer an opportunity for enhancing the economic efficiency and effectiveness of the expenditures. But, coordinating the interventions of multiple co-located assets brings some challenges to the decision-makers. For instance, the interventions' common practices, requirements, and applied technologies of roads structural elements and pavement surface, water pipes, and sewer pipes are different due to their dissimilar characteristics such as; deterioration rates, design service lives, environmental reactions, nature of usage, and Life-cycle Costs (LCC). Furthermore, there are different requirements associated with quality, safety, environmental, and health regulations. The core of integrated planning and funding of municipal projects should be represented through near-optimal coordination between the projects' interventions' timing, locations, types, and alternatives as well as fund allocation. Achieving a higher level of coordination among the co-located assets will eventually boost the municipal asset management efficiency and effectiveness and increase the opportunities to reduce the economic losses. Moreover, the higher the level of coordination is, the higher the opportunity to help in closing the infrastructure deficit in the long-term. Even though the above-mentioned studies suggest that even 1% savings on the annual huge infrastructure budget could save billions throughout the next two decades, both globally and nationally, the lack of adequate coordination among municipal projects is still a typical source of economic losses. Municipalities need more investigations on optimized planning and funding that maximizes the projects' coordination throughout the assets' life cycles to minimize the resulting economic losses and increase the financial savings.

Recently, it has been noticed that there is no clear definition of integrated asset management. The following definitions represent the different integrated asset management perspectives throughout the past decade:

a. Danylo and Lemer (1998) considered that the main role of an infrastructure asset management system is to work as *"*an *integrator"*, a system that can interact with and analyze the output of many different systems.
b. Shen and Spainhour (2001) emphasized that "the tools and methodologies for infrastructure life-cycle management should *integrate* environmental, economic, and technical issues into a total solution".
c. "All municipalities across Canada should apply an integrated approach to assess and evaluate their roads, sewer, and water systems" (InfraGuide 2003a; 2003b; 2003c; 2004; 2006). Moreover, InfraGuide (2006) recommended that treating the assets as one integrated system is the best practice for managing multiple infrastructure networks. Similarly, different InfraGuide volumes emphasized the importance of integrated management for the co-located road, sewer and water networks.
d. Adopting integrated multi-disciplinary approaches became a key requirement for implementing efficient and sustainable asset management (Halfawy 2008; 2010; Halfawy *et al.* 2008; Shahata and Zayed 2010).
e. The Institute of Asset Management in conjunction with the British Standards Institution published the first publicly available specification for optimized management of physical assets in 2004. Then, an update was developed by 50 organizations from 15 industry sectors in 10 countries (BSIgroup 2008). In the Publicly Available Specification (PAS 55), asset management is defined as "*the systematic and coordinated activities and practices through which an organization optimally and sustainably manages its assets and asset systems, their associated performance, risks, and expenditures over their life cycles for achieving its organizational strategic plan*" (BSIgroup 2015; Hastings 2014).
f. After the widespread adoption of PAS 55 in utilities, transport, and manufacturing industries, the International Standards Organization (ISO) accepted PAS 55 as the development basis of the new ISO 55000 international standards series. ISO 55000 was published in 2014 and it defined asset management as: "*coordinated activity of an organization to realize value from assets*" (ISO 2014; NAMS 2006; 2007; 2014; 2015).

From this standpoint, the mainstream of the integrated asset management research has been concentrating on several perspectives, which could be best summarized as follows:

1. System complexity: It focuses on enhancing the management and balance of the factors for both micro/project and macro/network levels (Houston 2014).
2. Financial reporting: It aims at optimizing the assets' intervention schedule to reach near-optimum funding decisions and trade-off different maintenance alternatives/schedules across the planning horizon (Halfawy 2008).
3. Information management: The integrated asset management represents an excellent example for the "Big Data" issue, which requires improving the data integration process across multiple departments (Michele and Daniela 2011).
4. Integration factors: The integrated asset management frameworks were restricted to specific areas such as; (1) Geographic Information System (GIS) integration systems (Halfawy 2010); (2) integrated risk-based decision-making (Shahata and Zayed 2016); and (3) integrated condition rating (Elsawah *et al.* 2014).
5. Conflicting perspectives: The integrated asset management could be taken from both the community perspective or the municipal perspective with changing objectives (Khan *et al.* 2015).

2.3 Optimization for Asset Management

Multi-objective optimization has been widely used in the infrastructure domain, especially in budget allocation, efficient expenditures' utilization, performance enhancement, and intervention planning and scheduling. Furthermore, the existence of uncertainties associated with deterioration pattern, economic situation (i.e. inflation rates, available budget, etc.), political views, etc. escalates the complexity of the problem (Frangopol and Liu 2007). Moreover, the fact that the problem comprises multiple stakeholders (i.e. municipalities, asset managers. end users, politicians) with conflicting preferences upsurges the intricacy of the problem and makes the trade-off difficult to reach consensus agreement among the conflicting stakeholders' preferences (Saad and Hegazy 2015a). Those preferences vary from one asset to another and from one stakeholder to another. They might include but not limited to; maximum network performance, minimal risk consequences, maximum intervention efficiency and effectiveness, minimal LCC, minimal social/user costs. Another issue is creating a balance between the conflicting stakeholders' objectives in both network and project level decisions

(Barco 1994; Uddin *et al.* 2013). Those decisions could be summarized in the 3W's questions: (1) which assets should be considered for intervention; (2) when should those interventions take place; and (3) what intervention type/strategy is required for each asset. The "Which" and "When" questions are the network level decisions. However, the "What" question is the project level decision. In business terms, the network level decisions represent the strategic and tactical levels of management, where strategic directions are guiding those decisions. However, the project level decisions represent the operational level of management, where several factors guide the final decision (i.e. asset in failing condition state will have to be reconstructed or replaced). The problem in hand includes: (1) multiple spatially-located assets (i.e. roads, water, and sewer networks) with varying deterioration patterns and service lives; (2) limited budget with lots of corridors requiring interventions; (3) manifold intervention types and strategies for each asset (i.e. preventive maintenance, minor repair, major rehabilitation, reconstruction, replacement, etc.); (4) trade-off between in-house sub-contracting and private partnership for undertaking the interventions; (5) interdependency among the assets' investigated in this study; and (6) varying performance expectations from the end users (Saad *et al.* 2017). Table 8-1 summarizes some of these research efforts, sorted in chronological and alphabetical order, within various sectors of civil infrastructure systems (transportation, water, sewer, coastal structures, and buildings) to provide the reader with sufficient context in framing the research problem and its contributions.

This section is devoted to discussing and analyzing the outcome of the studies highlighted in Table 8-1. Numerous scholars developed decision-making systems for different assets to solve various objectives. Several techniques were developed over the last decades such as; ELimination and Choice Expressing REality (ELECTRE) (Benayoun*et al.* 1966); Weighted sum model (Fishburn 1967); Weighted product model (Bridgman 1922; Miller and Starr 1969), Analytical Hierarchy Process (AHP) (Saaty 1980); Analytical Network Process (ANP) (Saaty 1996); Technique for Order of Preference by Similarity to Ideal Solution (TOPSIS) (Hwang and Yoon 1981); Compromise programming (CP) (Zeleny 1982); Preference Ranking Organization METHod (PROMETHEE) (Brans and Vincke 1985) and VIseKriterijumska Optimizacija I Kompromisno Resenje - Serbian: Multicriteria Optimization and Compromise Solution (VIKOR) (Opricovic 1998). Several scholars reviewed the multi-objective optimization research within the asset management domain (Alysson *et al.* 2018; Saidi *et al.* 2018; Mardani el al. 2016; 2015; Zavadskas *et al.* 2015a; 2015b; 2014; Frangopol and Soliman 2016; Kabir *et al.* 2014; Frangopol *et al.* 2012; Frangopol 2011; Hegazy *et al.*

2011). Research efforts were geared towards using optimization in solving various infrastructure problems. Based on the objective function, the optimization problems could be categorized into (1) multi-objective, and (2) single objective.

2.3.1 *Multi-objective: Discussion and Analysis*

2.3.1.1 *Multi-assets*

Numerous scholars developed multi-objective optimization models for multiple corridor infrastructure assets. The scholars utilized several techniques to overcome the huge search space issue. For instance, some scholars used a phased network manner, where the project level decisions were taken separately for each asset and then the results were used as an input for the network level trade-off analysis (Abu-Samra *et al.* 2018a; Osman *et al.* 2012). Other scholars used dynamic and integer programming to overcome the extended planning horizon issue; split the planning horizon into smaller ones; and model the project and network level decision variables (Abu-Samra *et al.* 2018a; El-Anwar *et al.* 2016a; 2016b). In terms of optimization techniques and algorithms, several techniques were utilized to overcome the multi-objective multi-asset inherited complexity. Some scholars used preemptive goal optimization (i.e. fragments the multi-objective problem into single objective ones, based on the objectives ranking, and once the desired objective outcome is reached, the system automatically turns to the 2nd one while respecting the outcome of the 1st objective through placing it as a constraint), non-preemptive goal optimization (i.e. minimize the deviations from the pre-set thresholds), Genetic Algorithms (GAs), pareto optimization to model the conflicting objectives issue via a percentile ranking approach as outlined in the evolutionary algorithms category within Table 2-1. Other scholars used mathematical optimization, mixed integer programming, simulation, system dynamics, casual loop diagram, and decision trees to solve the problem as outlined in the decision-making and mathematical/linear optimization categories within Table 2-1. Most of the scholars focused on performance, represented through condition or reliability; risk, represented through Probability of Failure (POF) and Consequences of Failure (COF); LCC, including direct and indirect/user costs; and return on investment, represented through improvement in performance vs. costs paid. The objectives were maximizing the performance or return on investment and minimizing the risks and LCC.

Table 2-1: *Summary of research related to multi-objective multi-assets optimization*

Research	Domain of application	Scale of application	Optimization type	Optimization tool	Objective(s)	Category
Abu-Samra *et al.* (2018a)	Roads, water, and sewer	Phased network level	Multi-objective	Integrated goal optimization, dynamic, and integer programming, and GAs	Minimize deviations from the budget and performance targets	Evolutionary algorithms
Abu-Samra *et al.* (2017a)	Roads, water, and sewer	Network level	Multi-objective	Preemptive goal optimization	Maximize reliability, minimize life-cycle costs, minimize economic losses	Evolutionary algorithms
Abu-Samra and Ahmed (2017)	Roads and water	Network level	Multi-objective	Non-preemptive goal optimization	Minimize financial, temporal, and condition deviations	Evolutionary algorithms
Abu-Samra *et al.* (2017b)	Roads, water, and sewer	Network level	Multi-objective	Non-preemptive goal optimization	Minimize deviations from annual budget and performance target	Evolutionary algorithms
Al-Anwar *et al.* (2016a)	Roads and bridges	Network level	Multi-objective	Mixed integer-liner programming and pareto optimization	Minimize the network recovery time and public expenditures	Mathematical/Linear optimization
Al-Anwar *et al.* (2016b)	Roads and bridges	Network level	Multi-objective	Mixed integer-liner programming and pareto optimization	Minimize the network recovery time and public expenditures	Mathematical/Linear optimization
Rashedi and Hegazy (2016a)	Roads, water, and sewer	Network level	Multi-objective	Casual loop diagrams and system dynamics	Maximize performance and minimize costs	Decision-making
CGI (2015)	Roads, water, and sewer	Network level	Multi-objective	Mathematical optimization	Minimize risks and maximize return of investment	Mathematical/Linear optimization
Osman (2015)	Roads, water, and sewer	Network level	Multi-objective	Non-preemptive goal optimization	Minimize deviations from the pre-defined targets	Evolutionary algorithms

Research	Domain of application	Scale of application	Optimization type	Optimization tool	Objective(s)	Category
Tscheikner-Gratl *et al.* (2015)	Roads, water, and sewer	Network level	Multi-objective	Decision tree	Maximize the street priority index	Decision-making
Elsawah *et al.* (2014)	Roads, water, and sewer	Network level	Multi-objective	Decision tree	Minimize risk consequences and maximize condition	Decision-making
Farran and Zayed (2015)	Roads, water, and sewer	Network level	Multi-objective	Integrated markov chains and GAs	Minimize life-cycle costs and maximize performance	Evolutionary algorithms
Osman *et al.* (2012)	Water and sewer	Phased project and network level	Multi-objective	GAs with pareto optimization	Minimize risk exposure and condition assessment cost	Evolutionary algorithms
Ali *et al.* (2012b)	Water and sewer	Project and network level	Multi-objective	Integrated markov chains and GAs	Minimize inspection costs	Evolutionary algorithms
Amador and Magnuson (2011)	Roads, water, and sewer	Network level	Multi-objective	Integrated classical time-space adjacency modeling, heuristic simulation, and mathematical optimization	Minimize the life-cycle costs and service disruption	Mathematical/Linear optimization
Atef *et al.* (2011)	Water and sewer	Network level	Multi-objective	Integrated markov chains and GAs	Maximize condition and minimize costs	Evolutionary algorithms
Atef *et al.* (2010)	Water and sewer	Network level	Multi-objective	Partially observable markov decision process	Minimize the cost and maximize the reliability	Decision-making
Osman (2005)	Roads, water, and sewer	Network level	Multi-objective	Monte Carlo simulation	Minimize risks and maximize return of investment	Decision-making
Dicdican *et al.* (2004)	Roads and bridges	Network level	Multi-objective	GAs	Minimize short and long-term costs and maximize service life	Evolutionary algorithms
Halfawy *et al.* (2002)	Roads, water, and sewer	Network level	Multi-objective	Integrated GIS and mathematical optimization	Minimize cost and maximize condition	Mathematical/Linear optimization

2.3.1.2 *Single asset*

The multi-objective for single asset research received more attention than the multi-assets, where a multitude of scholars developed multi-objective optimization systems for roads, bridges, water and sewer networks, buildings, and subways. The scholars utilized several optimization algorithms and decision-making techniques to model their indicators and accordingly solve the problem. For instance, some scholars used bi-level goal optimization for reaching optimal project and network-level decisions. Several modeling methods (i.e. penalty and compromise methods) were used to minimize the financial and performance deviations. The penalty method uses the weighted sum technique to combine multiple objectives into a single function after assigning different weights for each objective to create pareto-optimal solutions. However, the compromise method is founded on the ε-constraint technique, which relies on maximizing/minimizing one of the objectives and setting the remaining objectives as constraints (Frangopol and Liu 2007; Mavrotas 2009; Colson et al. 2007). Other scholars utilized mathematical optimization in the General Algebraic Modeling System (GAMS) modeling environment with C programming-based solver using Simplex method (CPLEX) to formulate the objectives in the form of equalities, such that they should meet certain limits as outlined in the mathematical/linear optimization category within Table 2-2 (GAMS 2017; IBM 2009; Saad el al. 2017; 2016; Scheinberg and Anastasopoulos 2009). Other scholars used goal optimization, GAs, memetic algorithms, particle swarm, ant colony systems, and Shuffled Frog Leap (SFL) to solve the problem and arrive at a near-optimal intervention plan as outlined in the evolutionary algorithms category within Table 2-2. Another pool of researchers used Multi-Attribute Utility Theory (MAUT), decision tree, benefit/cost analysis, microeconomics-based heuristics, neural networks, integer programming, and AHP to acquire the weights of the factors and select their intervention plans accordingly as outlined in the decision-making category within Table 2-2. Given the fact that the scholars were dealing with a single asset, new operational-based set of objectives was recognized along with the performance, risk, LCC, and return on investment. This operational-based set included the repair time, resources, maintenance efficiency, safety, damage detection delay, and resilience. The objectives were always a mixed blend of the pre-mentioned objectives, where LCC, risks, repair time, resources were aimed to be minimized whereas performance, return on investment, maintenance efficiency, safety, and resilience were aimed to be maximized.

Table 2-2: *Summary of research related to multi-objective single asset optimization*

Research	Domain of application	Scale of application	Optimization type	Optimization tool	Objective(s)	Category
Salah *et al.* (2018)	Buildings	Project level	Multi-objective	Goal optimization and GAs	Maximize the level of service and minimize the LCC	Evolutionary algorithms
Abu-Samra *et al.* (2017c)	Roads	Network level	Multi-objective	Integrated goal optimization and GAs	Minimize deviations from the KPIs' thresholds	Evolutionary algorithms
Frangopol *et al.* (2017)	Bridges	Network level	Multi-objective	Integrated probabilistic life-cycle optimization, MAUT, and risk	Maximize the network performance and minimize the costs	Decision-making
Kim and Frangopol (2017)	Bridges	Network level	Multi-objective	Weighted sum method and GAs with pareto optimization	Minimize the damage detection delay, probability of failure, life-cycle cost, and maximize the service life	Decision-making
Osman *et al.* (2017)	Water	Network level	Multi-objective	Integrated discrete event simulation and GAs	Minimize the repair time, cost, and pipe break impact	Evolutionary algorithms
Saad el al. (2017)	Roads	Network level	Multi-objective	Bi-level goal optimization with pareto (penalty and compromise methods)	Minimize deviations from the pre-defined targets	Mathematical/ Linear optimization
Saad el al. (2016)	Roads	Network level	Multi-objective	Bi-level goal optimization using General Algebraic Modeling System (GAMS)/CPLEX	Minimize deviations from the pre-defined targets	Mathematical/ Linear optimization
Sabatino *et al.* (2016)	Bridges	Network level	Multi-objective	GAs	Maximize performance, minimize cost and failure consequences	Evolutionary algorithms
Abu-Samra (2015)	Roads	Phased project and network level	Multi-objective	Integrated goal optimization and GAs	Minimize deviations from the KPIs' thresholds	Evolutionary algorithms
Dong *et al.* (2015)	Bridges	Project level	Multi-objective	Integrated benefit/cost analysis, MAUT, and GAs	Maximize the sustainability utility and minimize maintenance cost and failure consequences	Evolutionary algorithms

Research	Domain of application	Scale of application	Optimization type	Optimization tool	Objective(s)	Category
Matar *et al.* (2017)	Water	Project level	Multi-objective	Systems engineering and System of Systems (SoS)	Maximize the project sustainability index	Decision-making
Saad and Hegazy (2015a)	Buildings	Network level	Multi-objective	Micro economic-based heuristic	Maximize the benefit per dollar spent	Mathematical/ Linear optimization
Sabatino *et al.* (2015)	Bridges	Project level	Multi-objective	GAs	Maximize the sustainability utility and minimize maintenance cost	Evolutionary algorithms
Barone and Frangopol (2014)	Bridges	Project level	Multi-objective	GAs	Maximize structural performance and minimize maintenance costs	Evolutionary algorithms
Elhadidy *et al.* (2015)	Roads	Network level	Multi-objective	GAs with pareto optimization	Maximize the condition and minimize the cost	Evolutionary algorithms
Marzouk and Omar (2013)	Sewer	Network level	Multi-objective	GAs	Maximize condition and minimize costs	Evolutionary algorithms
Salman *et al.* (2013)	Water	Network level	Multi-objective	Integrated Unsupervised Neural Networks (UNN) and Mixed Integer Non-Linear Programming (MINLP)	Minimize the repair time and maximize reliability	Mathematical/ Linear optimization
Sitzabee and Harnly (2013)	Roads	Network level	Multi-objective	Goal optimization	Maximize the priority index	Evolutionary algorithms
Ward and Savic (2013)	Sewer	Project level	Multi-objective	Integrated AHP and MAUT	Maximize structural condition and minimize costs and risk	Decision-making
Bocchini and Frangopol (2012)	Bridges	Network level	Multi-objective	GAs	Maximize resilience; minimize time and restoration costs	Evolutionary algorithms
Orabi *et al.* (2012)	Roads	Network level	Multi-objective	GAs	Minimize reconstruction costs and network disruption	Evolutionary algorithms
Shehab-El-deen and Moselhi (2011)	Sewer	Network level	Multi-objective	MAUT	Minimize the cost and time	Decision-making

Research	Domain of application	Scale of application	Optimization type	Optimization tool	Objective(s)	Category
Okasha and Frangopol (2010)	Bridges	Project level	Multi-objective	GAs	Minimize dysfunctionality, maximize redundancy, and minimize life-cycle costs	Evolutionary algorithms
Zhao *et al.* (2010)	Buildings	Network level	Multi-objective	Geometrical pareto selection and double neighbored crossover	Maximize the network performance and minimize the costs	Evolutionary algorithms
Alvisi and Franchini (2009)	Water	Network level	Multi-objective	GAs with pareto optimization	Minimize repair costs and water losses	Evolutionary algorithms
Liu and Frangopol (2009)	Bridges	Network level	Multi-objective	GAs	Maximize the network reliability and minimize the life-cycle costs	Evolutionary algorithms
Mavrotas (2009)	Buildings	Project level	Multi-objective	E-Constraint Method using lexicographic/preemptive procedure	Minimize the total cost, maximize the level of service, maximize profit	Mathematical/ Linear optimization
Orabi *et al.* (2009)	Roads	Project level	Multi-objective	GAs	Minimize reconstruction costs	Evolutionary algorithms
Scheinberg and Anastasopoulos (2009)	Roads	Phased project and network level	Multi-objective	Mathematical optimization and mixed integer programming	Minimize costs and maximize condition	Mathematical/ Linear optimization
Muschallah (2008)	Sewer	Network level	Multi-objective	GAs with pareto optimization	Maximize condition and minimize costs	Evolutionary algorithms
Wu and Flintsh (2008)	Roads	Project level	Multi-objective	GAs	Maximize the level of service and minimize the preservation costs	Evolutionary algorithms
Alvisi and Franchini (2007)	Water	Network level	Multi-objective	GAs	Minimize cost and maximize performance	Evolutionary algorithms
Frangopol and Liu (2007)	Bridges	Network level	Multi-objective	GAs	Maximize condition and safety and minimize life-cycle costs	Evolutionary algorithms

Research	Domain of application	Scale of application	Optimization type	Optimization tool	Objective(s)	Category
Guistolisi *et al.* (2006)	Water	Network level	Multi-objective	Benefit/Cost analysis	Maximize benefit/cost ratio	Decision-making
Elbeltagi *et al.* (2005b)	Bridges	Network level	Multi-objective	GAs, memetic algorithms, particle swarm, ant colony systems, and SFL	Maximize performance and efficiency and minimize time, resources, and cost	Evolutionary algorithms
Liu and Frangopol (2005)	Bridges	Network level	Multi-objective	Event tree analysis and GAs	Minimize the net present value of the maintenance costs and maximize the network performance	Evolutionary algorithms
Hegazy *et al.* (2004a)	Bridges	Phased project and network level	Multi-objective	GAs	Maximize the performance and minimize the cost	Evolutionary algorithms
Fwa *et al.* (2000)	Roads	Project level	Multi-objective	GAs	Minimize maintenance costs, maximize condition and maintenance efficiency	Evolutionary algorithms
Hegazy *et al.* (1994)	Roads	Network level	Multi-objective	Enhanced backpropagation for neural networks using heuristics	Maximize the network performance	Evolutionary algorithms

2.3.2 *Single objective: Discussion and Analysis*

2.3.2.1 *Multi-assets*

The single objective for multi-assets research has received less attention as opposed to the single asset one given the fact that the assets' coordination increases the scale of the problem and initiates the need for multiple objectives to address the different assets' nature (i.e. service lives, deterioration mechanisms, intervention strategies, etc.). Few scholars developed optimization models for co-located systems such as; roads and bridges; and roads, water and sewer networks. Some of them utilized mathematical optimization and GAs to reach their objectives as outlined in the mathematical/linear optimization and evolutionary algorithms categories within Table 2-3. Other scholars used ranking techniques such as; decision trees and mixed Delphi and AHP with k-means clustering to assign weights among their assets and rank the corridors for interventions as outlined in the decision-making category within Table 2-3. Even though there is a multitude of important objectives that need to be met, some scholars preferred single objective modeling and placed the other objectives as "soft" or "hard" constraints after defining their corresponding limits. It was recognized that the scholars followed one of those two schools: (1) minimize the LCC or risks and place a minimally acceptable threshold for the performance; or (2) maximize the performance, represented through condition or reliability, and place a constraint on the expenditures not to exceed the annual budget.

Table 2-3: *Summary of research related to single objective multi-assets optimization*

Research	Domain of application	Scale of application	Optimization type	Optimization tool	Objective(s)	Category
Saad and Hegazy (2017a)	Roads and bridges	Network level	Single objective	Enhanced benefit/cost analysis	Maximize the benefit/cost ratio	Decision-making
Elsawah *et al.* (2016)	Water and sewer	Network level	Single objective	Ranking method and dynamic weighting system	Prioritize the corridors for repair based on the risk index	Decision-making
Shahata and Zayed (2016)	Roads, water, and sewer	Network level	Single objective	Mixed Delphi and AHP and K-means clustering	Minimize risk index	Decision-making
Fathy *et al.* (2015)	Water and sewer	Project level	Single objective	Integrated hierarchical Artificial Neural Network (ANN) and GAs	Minimize the ANN training error to select the best rehabilitation strategy	Evolutionary algorithms
Ramachandran *et al.* (2015)	Roads and bridges	Network level	Single objective	Nearest neighbor algorithm	Minimize resilience time	Evolutionary algorithms
Hegazy and Saad (2014)	Buildings and roads	Phased project and network level	Single objective	Mathematical optimization	Maximize condition improvement	Mathematical/ Linear optimization
Mostafa and El-Gohary (2014)	Roads and bridges	Network level	Single objective	Decision tree	Maximize benefits	Decision-making
Shahata and Zayed (2010)	Roads, water, and sewer	Network level	Single objective	GAs	Minimize repair costs	Evolutionary algorithms
Elhakeem and Hegazy (2005)	Roads, water, and sewer	Network level	Single objective	Nomographs	Minimize the cost to allocate the manpower resources	Evolutionary algorithms

2.3.2.2 *Single asset*

Single objective research for single asset received more attention than the multi-assets. Several scholars developed single objective optimization systems for roads, bridges, water and sewer networks, buildings, coastal structures, and subway. Scholars used several optimization modeling techniques and algorithms to reach their objectives. For instance, some scholars utilized sequential optimization, mathematical optimization through GAMS modeling environment, SFL, segmented GAs, and GAs to solve the single objective problem as outlined in the mathematical optimization and evolutionary algorithms categories within Table 2-4. Other scholars utilized linear programming, heuristics, MAUT, AHP, ANP, Fuzzy ANP (FANP), Artificial Neural Network (ANN), markov chains, simulation, microeconomics, simple ranking, and loss-aversion to model their objectives and solve the problem as outlined in the decision-making category within Table 2-4. Similar to the single objective for multi-assets, the scholars followed one of two schools: (1) minimize the LCC or risks and place a minimal acceptable threshold for the performance; and (2) maximize the performance, represented through condition or reliability, and place a constraint on the expenditures not to exceed the annual budget. Few scholars merged several objectives into one indicator such as; resilience index, deterioration index, cost-effectiveness, efficiency of expenditure, gain per dollar, etc. Those indices are extracted from the main objectives and they are amalgamated using weights of importance among the blended objectives.

Table 2-4: *Summary of research related to single objective single asset optimization*

Research	Domain of application	Scale of application	Optimization type	Optimization tool	Objective(s)	Category
Ghodoosi *et al.* (2018)	Bridges	Project level	Single objective	GAs	Minimize the equivalent uniform annual cost over the bridge life-cycle	Evolutionary algorithms
Ismaeel and Zayed (2018)	Water	Network level	Single objective	GAs	Maximize the network performance	Evolutionary algorithms
Kaddoura *et al.* (2018)	Sewer	Project level	Single objective	MAUT	Prioritize the corridors for rehabilitation based on the aggregated condition index	Decision-making
Abu-Samra (2017b)	Buildings	Network level	Single objective	Cash flow analysis and GAs	Select the optimal schedule to minimize the risk impact on the cash flow	Evolutionary algorithms
Al-Zahab *et al.* (2017)	Water	Network level	Single objective	GAs	Maximize the benefit/cost ratio for prioritizing the leak repairs	Evolutionary algorithms
Dong and Frangopol (2017)	Bridges	Network level	Single objective	Integrated fragility analysis, latin hypercube sampling, and weibull	Maximize the benefit/cost ratio	Decision-making
Marzouk and Abdel Hamid (2017)	Water	Network level	Single objective	Integrated simo procedure and decision tree	Prioritize the corridors for repair	Decision-making
Mohammed *et al.* (2017)	Roads	Network level	Single objective	GAs	Maximize resilience index	Evolutionary algorithms
Saad and Hegazy (2017b)	Buildings	Network level	Single objective	Microeconomic-based heuristic approach	Maximize the efficiency of expenditure	Mathematical/ Linear optimization
Abu-Samra *et al.* (2016)	Water	Project level	Single objective	Integrated discrete event simulation and GAs	Minimize the risk index represented by consequences of failure and leak severity	Evolutionary algorithms
Hawari *et al.* (2017)	Sewer	Project level	Single objective	Integrated FANP and monte carlo simulation	Prioritize the corridors for rehabilitation	Decision-making

Research	Domain of application	Scale of application	Optimization type	Optimization tool	Objective(s)	Category
Ismaeel and Zayed (2016)	Water	Network level	Single objective	GAs	Maximize the network performance	Evolutionary algorithms
Kaddoura *et al.* (2016)	Sewer	Project level	Single objective	MAUT	Prioritize the corridors for rehabilitation based on the aggregated condition index	Decision-making
Rashedi and Hegazy (2016b)	Buildings	Phased project and network level	Single objective	Mathematical optimization (GAMS/CPLEX) and GAs	Minimize deterioration index	Mathematical/ Linear optimization
El-Hakea and Abu-Samra (2015)	Coastal structures	Project level	Single objective	GAs	Minimize the life-cycle costs	Evolutionary algorithms
El-Hakea *et al.* (2015)	Coastal structures	Network level	Single objective	GAs	Minimize the network life-cycle costs	Evolutionary algorithms
Marzouk *et al.* (2015)	Water	Network level	Single objective	Integrated Geographic Information System (GIS), simo procedure and decision tree	Prioritize the corridors for repair	Decision-making
Saad and Hegazy (2015b)	Roads	Network level	Single objective	Loss-aversion	Maximize the gain within the limited budget	Mathematical/ Linear optimization
Zdenko *et al.* (2015)	Water	Network level	Single objective	Decision tree	Maximize network performance	Decision-making
Abouhammad and Zayed (2014)	Subway	Network level	Single objective	FANP ranking	Prioritize the repair of the subway stations	Decision-making
El-Hakea *et al.* (2014)	Coastal structures	Project level	Single objective	Integrated ANN and GAs	Minimize the training error	Evolutionary algorithms
Khan *et al.* (2014)	Water	Network level	Single objective	Decision tree	Prioritize the corridors for repair	Decision-making
Azeez *et al.* (2013)	Sewer	Network level	Single objective	Fuzzy and simulation-based ranking	Minimize the life-cycle costs	Decision-making

Research	Domain of application	Scale of application	Optimization type	Optimization tool	Objective(s)	Category
Elsayed and Zayed (2013)	Water	Network level	Single objective	Integrated AHP and MAUT	Prioritize the water main rehabilitation projects	Decision-making
Deco and Frangopol (2013)	Bridges	Network level	Single objective	Integrated fragility analysis, latin hypercube sampling, and weibull	Minimize the network life-cycle risks	Decision-making
Hegazy and Rashedi (2013)	Buildings	Network level	Single objective	GAs clustered segmentation and GAMS/CPLEX	Maximize the network performance	Evolutionary algorithms
Mohamed and Zayed (2013)	Water	Network level	Single objective	Integrated MAUT and AHP	Prioritize the corridors for fund allocation	Decision-making
Zayed and Mohamed (2013)	Water	Network level	Single objective	Integrated MAUT and AHP	Prioritize the corridors' repair based on the budget priority index	Decision-making
Zhang *et al.* (2013)	Roads	Network level	Single objective	Dynamic programming	Minimize the life-cycle costs	Decision-making
Adey *et al.* (2012)	Roads	Project level	Single objective	Mathematical optimization	Maximize net benefits	Mathematical/ Linear optimization
Ammar *et al.* (2012)	Water	Network level	Single objective	Integrated Day–Stout–Warren (DSW) algorithm and the vertex method	Minimize the life-cycle costs	Evolutionary algorithms
Fares *et al.* (2012)	Roads	Project level	Single objective	GAs	Minimize costs	Evolutionary algorithms
Farran and Zayed (2012)	Subway	Network level	Single objective	Dynamic markov and GAs	Minimize the life-cycle costs	Evolutionary algorithms
Hegazy *et al.* (2012)	Roads	Network level	Single objective	Heuristic approach	Minimize the life-cycle costs and prioritize the corridors for repair	Mathematical/ Linear optimization
De la Garza *et al.* (2011)	Roads	Network level	Single objective	Mathematical optimization	Maximize network performance	Mathematical/ Linear optimization
Shahata and Zayed (2011)	Water	Project level	Single objective	Simulation-based life-cycle costs and decision tree	Minimize the life-cycle costs	Decision-making

Research	Domain of application	Scale of application	Optimization type	Optimization tool	Objective(s)	Category
Ammar *et al.* (2010)	Water	Network level	Single objective	Integrated DSW algorithm and fuzzy set theory	Minimize the life-cycle costs	Evolutionary algorithms
Moselhi *et al.* (2010)	Water	Network level	Single objective	AHP decision-making	Maximize the level of service within the available budget	Evolutionary algorithms
El-behairy *et al.* (2009)	Bridges	Network level	Single objective	Sequential optimization	Maximize the network performance	Decision-making
Shahata and Zayed (2009)	Water	Network level	Single objective	Monte carlo simulation	Minimize the life-cycle costs	Evolutionary algorithms
Dridi *et al.* (2008)	Water	Network level	Single objective	GAs	Minimize the life-cycle costs	Evolutionary algorithms
Karlafits *et al.* (2007)	Bridges	Network level	Single objective	GAs	Maximize level of service	Evolutionary algorithms
Al-Barqawi and Zayed (2006a)	Water	Network level	Single objective	Integrated AHP and ANN	Maximize the network performance	Decision-making
Chootinan *et al.* (2006)	Roads	Project level	Single objective	Stochastic simulation and GAs	Maximize the level of service	Evolutionary algorithms
El-behairy *et al.* (2006)	Bridges	Network level	Single objective	GAs and Shuffled Frog Leaping (SFL)	Minimize the life-cycle costs	Evolutionary algorithms
Hegazy (2006)	Bridges	Network level	Single objective	GAs	Minimize the life-cycle costs	Evolutionary algorithms
Hegazy (2005)	Roads	Network level	Single objective	GAs	Minimize the life-cycle costs	Evolutionary algorithms
Morcous and Lounis (2005)	Bridges	Network level	Single objective	Markov chains and GAs	Minimize the life-cycle costs	Evolutionary algorithms
Abaza *et al.* (2004)	Roads	Network level	Single objective	Markovian non-linear programming	Maximize the network condition within the budget	Evolutionary algorithms
Hegazy *et al.* (2004b)	Roads	Network level	Single objective	GAs	Maximize the network performance	Evolutionary algorithms
Hegazy *et al.* (2003)	Buildings	Network level	Single objective	GAs	Minimize the costs with optimal resource allocation	Evolutionary algorithms

Research	Domain of application	Scale of application	Optimization type	Optimization tool	Objective(s)	Category
Tong *et al.* (2001)	Buildings	Network level	Single objective	GAs	Minimize replacement costs	Evolutionary algorithms
Miyamoto *et al.* (2000)	Bridges	Project level	Single objective	GAs with ε-constraint method	Maximize performance (capability and durability)	Evolutionary algorithms
Liu and Wang (1996)	Roads	Network level	Single objective	Linear programming	Maximize the network performance	Mathematical/ Linear optimization

2.3.3 *Main Findings and Limitations*

Even though single objective optimization has been widely used in the last decade, yet it does not support the transition from an "asset stewardship" approach, which is condition and cost centric, to an "asset serviceability" approach, which considers the cost, LOS, and risk exposure, as it is either cost or condition centric. Furthermore, existing multi-objective models are limited and need further enhancements in several areas. Those limitations could be summarized as follows:

1. Relying on a single objective and placing the other objectives as constraints will not result in a near-optimal solution for the constraint-placed objectives (i.e. when the annual budget is set as a constraint, the model will not result in the minimal LCC, but only a solution that meets the value placed as a constraint).
2. Some scholars tried to indirectly integrate multiple objectives into one indicator (i.e. benefit/cost ratio, etc.) for prioritizing the intervention of the corridors. Even though this technique had some potential, the fact that scholars relied on assigning weights of importance among the objectives increased the subjectivity and indirectly guided the results towards the objectives with higher weights of importance.
3. Losing the opportunity to undertake trade-off analysis and compare the fitness of different solutions with respect to the different objectives.
4. Missing the opportunity to carry out pareto optimization; evaluate different near-optimal solutions (i.e. minimal cost, maximum performance); and select an intermediate solution that fits the conflicting objectives.
5. Failure to fulfill the requirements of different decision-makers (i.e. politicians, asset managers, end users, maintenance contractors, etc.), as the model indirectly forces the selection of one preference over the others.
6. Computational complexity was a common issue among most of the scholars due to the extended planning horizon; multiple assets with varying service lives and deterioration mechanisms; numerous intervention strategies; and a huge pool of corridors. Those issues expanded the search space, which in return increased the running time.
7. Some scholars used deterministic modeling and failed to account for the uncertainties associated with the assets' deterioration as well as their costs.

8. Some scholar focused on extreme disastrous events (i.e. hurricanes, earthquakes, and tsunamis) and did not account for the typical aging deterioration while planning their interventions.
9. Some scholars utilized simple ranking techniques such as; decision trees, to solve the problem, which increases the subjectivity to account for uncertainties as well as its' inability to handle large-scale networks of assets.
10. Some scholars did not consider the LCC while planning the corridor interventions, which is a key aspect that guides the decision-making process.
11. Some scholars developed a network-level decision-making system without accounting for project-based decisions (i.e. preventive maintenance for roads, leak repair for pipes, cracks repair in buildings, etc.)
12. Some scholars relied on the current condition only, without accounting for future deterioration while planning their interventions. This obstructed them to see the big picture of the situation in hand and thus blocked them from taking informed intervention decisions.
13. Some scholars did not account for the time while modeling their indicators and just ranked the corridors for repair, based on their current condition state.
14. Fragmented optimization formulation, such that project and network-level decisions are handled in two separate models, and pre-defined project level rehabilitation types are used as fixed input to the network-level model.
15. Some scholars utilized complex mathematical formulations that encountered several scalability issues related to: (1) handling large-scale networks of infrastructure assets; and (2) inability of determining the optimal intervention type and timing for each asset.
16. Since the problem in hand deals with conflicting objectives (i.e. minimal cost, maximum performance, etc.), scholars used weights of importance to amalgamate the objectives and rank the corridors accordingly. Yet, those weights might vary among the different decision-makers, based on their preferences.

2.4 Municipal Contractual Practices

Public infrastructure impacts the communities from the water they drink to the roads they drive on. The quality and reliability of those assets play a pivotal role in determining the quality of life. Thus, municipalities are continuously challenged with maintaining the assets to meet the taxpayers' expectations. In many cases, municipalities do not have enough resources or expertise to undertake the required actions and meet the end user's quality expectations. Accordingly, contracts take place to guide the relationship between municipalities and contractors to frame the rights and responsibilities of both parties. The municipal contractual practices highly impact the infrastructure LCC and performance. They vary from one municipality to another and from one department to another. There are numerous contractual practices such as; in-house, direct award, tendering, sub-contracting, Public-Private Partnership (PPP), PBC, etc. The in-house contracts refer to the works that are carried out by the employer. Direct award contracts "*occur when a contract is awarded to a contractor without competition, or where there is a material change to an existing contract*" (UK 2017). Most public projects should, in most cases, be subject to competition to ensure the best value for money. Direct award contracts are also known as "Single Tender Actions" and take place when a contract is awarded to a contractor without competition. In most cases, the municipalities are obliged to publish all the direct award contracts for which they are responsible for, with values greater than a pre-set value, which varies from one municipality to another. However, this type of contract is rarely used to ensure transparency for public projects or guarantee fair competition to obtain the best value of the taxpayers' money (Government of Canada 2013).

Tendering is a commonly-used type of contract and it has three types: (1) open tendering, (2) selective tendering, and (3) negotiated tendering (Constructor 2017). The 1st type "open tendering" allows employers to advertise their proposed projects and permit all the interested contractors to apply for tender documents. Sometimes, employers call for a deposit from applicants, which is returned on receipt of a bona fide tender. However, this method wastes the contractors' resources since many contractors may spend time preparing tenders and lose. Furthermore, knowing that their chances of gaining the contract are small, contractors may not study the contract in details to work out their minimum price, but simply quote a price that will be certain to bring them profit, in case awarded the contract. Thus, employers may receive only "a lottery of prices", which is not necessarily the lowest price. If they choose the lowest tender, they take the risk of an improperly studied contract to appraise the risks involved; or the tenderer might not have the technical or financial resources to successfully complete the work. Cost consultants may think about the risks that all such low bids could prove unsatisfactory, but they cannot advise the employer what another bid to accept because they lack the certainty of information on the submitted bids. The 2nd type "selective tendering" allows employers to advertise their projects and invite contractors to apply and be shortlisted to bid for the project. The selected contractors should meet the pre-qualification criteria, set prior to the bidding invitation. The advantage of this type is the guarantee that the selected contractors have adequate experience, are financially sound, and have the resources and skills to carry out the work. Moreover, it motivates the contractors to thoroughly study the tender documents and put forward their keenest prices, given that they have reasonable chances of gaining the contract. However, since contractors have all been pre-qualified, it is difficult to reject the lowest bid, even if it appears dubiously low unless it is due to some obvious mistake. One of the key issues with both open and selective tendering is that contractors' circumstances can change after tender submission. They are prone to either lose other contracts, which might affect their financial stability; or succeed in other tenderers and thus, would not have enough skilled resources to deal with all the work they were awarded. Finally, the 3rd type "negotiated tenders" function through employers inviting contractor of their choice to submit prices for a project. In most cases, this type of tenders is used for specialized work or when there is a very tight deadline or emergency works. In that case, the selected contractors have good chances of being satisfactory given the previous satisfactory work performed with the municipality. When invited to tender, the contractor submits their price, and all the queries are discussed and usually settled without difficulty. Thus, mistakes in pricing can be reduced given that both the engineer (cost consultant), advising the employer, and the contractor are confident that the job should be completed within the budget if no unforeseen troubles arise. However, negotiated tenders for public works are rare because the standing rules of the public authorities do not normally permit them. Given the fact that tendering is one of the commonly used types and with the objective of increasing the contractors' selection transparency, numerous scholars developed contractors' selection procedures. For instance, El-Abbasy *et al.* (2013) developed a contractor selection model for roads using integrated simulation and ANP. Similarly, Abdelrahman *et al.* (2008) developed a best-value model to rank the contractors applying for tenders. Other scholars developed prioritization models to evaluate the tenders and rank the contractors accordingly (Shrestha *et al.* 2017; Fong and Choi 2000; Menard and Saussier 2000).

Sub-contracting is another way of transferring the risk to a sub-contractor. It is "*the practice of assigning part of the obligations and tasks under a contract to another party known as a subcontractor*" (Investopedia 2017). Sub-contracting is used in mega-scale projects when the range of required capabilities for a project is too diverse to be carried out by a single general contractor. In such cases, subcontracting parts of the project may assist in keeping costs under control and mitigate the overall project risk.

PPP is a "*long-term, performance-based approach to procuring public infrastructure that can enhance governments' ability to hold the private sector accountable for public assets over their expected lifespan*" (PPP Canada 2017). They aim at engaging the private sector in delivering and operating huge infrastructure projects to benefit from their expertise, innovation, discipline, and incentives of capital markets. It transfers a huge share of the risks, associated with infrastructure development (i.e. costs overruns, schedule delays, unexpected maintenance, and hidden assets' defects) to the private sector. The idea of the contract is engaging the private sector in a bundled contract across the asset's life-cycle. The contractual payments for operations and/or maintenance are linked to the quality of the original construction. The key features of PPP could be summarized as follows: (1) governments do not pay for the asset until it is built and operational; (2) huge portion of the contract is paid out over a long term, and only if the asset is properly maintained and performs well under the contractual KPIs; and (3) LCC are known upfront, such that taxpayers are not bearing the risk of any costs that might unexpectedly arise during the contract period. PPP is widely used in mega-scale infrastructure projects across Canada's provinces (El-Gohary *et al.* 2006).

2.4.1 *Performance-Based Contracts (PBC)*

PBC is a special type of contracts that was conceptually designed to increase both the efficiency and effectiveness of infrastructure maintenance. It is similar to the PPP but limited to the operation and maintenance of the assets, without construction. Thus, it targets the operation and maintenance of the already-built infrastructure. It is "*a type of contract that focuses on the outputs, quality, and outcome of the service provision and may tie at least a portion of the maintenance contractors' payment as well as any contract extension or renewal to their achievement.*" (Martin 2003). In other words, it is a "*type of contract under which the maintenance contractor undertakes to plan, program, design, and implement maintenance activities to achieve specified short and long-term condition standards for a fixed price, subject to specified risk allocation*" (Frost and Lithgow 1998). Simply, it sets forth the final expected performance rather than directing the maintenance contractor with the methods and materials to achieve the expected performance. Before the PBC development, there were three types of specifications used for construction and maintenance contracts: (1) methods-based specifications, where the contract defines the exact construction and maintenance methods and sequence in either constructing or maintaining the asset. As a result, the maintenance contractor should be just performing the job as specified in the contract and is deemed to be fulfilling the contractual obligations only if the pre-defined method and sequence of work are followed; (2) material properties-based specifications, where the contract identifies several properties in which the asset should meet. The maintenance contractor is said to comply with the pre-defined material properties regardless the construction/maintenance method used to meet those properties; and (3) method and material properties-based specifications, where the contract combines and integrates the above-mentioned types and specifies both the method and materials to reach the optimal performance and apply the best maintenance strategies (Ozbek 2004). It is apparent that the main aim of applying these kinds of contracts was to "*provide a roadway that will carry traffic over a long service life*" (Stephens *et al.* 1998). However, these contract types never clearly state that "*the roadway needs to provide a long and useful service life*" (Ozbek 2004). They just mentioned the quality of each element solely without correlating them to the overall performance of the asset under the contract. However, PBC assesses the maintenance contractors in terms of performance, not in terms of the level of exerted efforts.

It has been applied to the pavement sector in numerous countries (i.e. Canada 1988, Argentina 1990, Finland 1998, Zambia 1999, etc.). Given its' limited application to other infrastructure sectors, the roads will be taken as an example to explain the contractual scheme and setup. Typically, PBC covers an array of activities needed to maintain a road service quality level for users. The main PBC activities could be displayed in Figure **2-2** (World Bank 2002). Those activities include (1) initial rehabilitation works, which are carried out prior to signing the contract for bringing-up the road to certain pre-defined standards; (2) regular maintenance services, which includes all the activities related to the management and evaluation of the road under the contract as well as the physical activities to maintain the agreed service quality levels; (3) improvement works, which are specified by the employer to add new characteristics to the roads (i.e. adding a lane for new traffic; safety or any other considerations; etc.); and (4) emergency works, which include any activity needed to reinstate the roads after any damages resulting from unforeseen natural phenomena with imponderable consequences such as; extreme freeze and thaw, strong storms, flooding, earthquakes, etc.

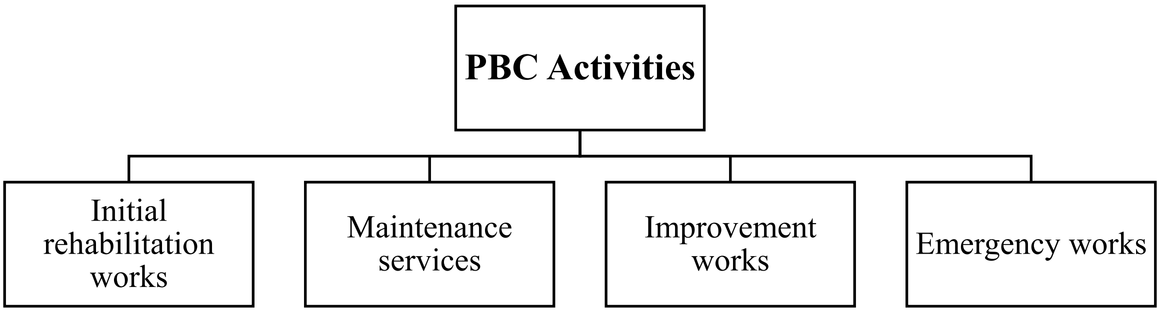


Figure 2-2: *PBC activities for roads*

The financial tender should be presented under the following five categories: (1) initial rehabilitation works, which is represented through a lump-sum amount. The maintenance contractor should indicate the quantities of measurable outputs that will be executed to achieve the pre-defined contractual performance standards; (2) maintenance services, which is represented in a form of monthly lump-sum payment in case of meeting the pre-defined contractual KPIs' thresholds; (3) improvement works, which is represented in a form of unit prices for each improvement work type. The payment for the improvement works will be calculated based on these unit prices defined by the maintenance contractor in the signed contract documents; (4) emergency works, which is represented through unit prices in a conventional bill of quantities. The payment for the emergency works is decided on a case-by-case basis given the uncertainty of the estimated quantities; and (5) price adjustment, which is a clause defined in the contract to compensate the maintenance contractors for any increase in the cost indices. This clause is applicable to all the above-mentioned prices and activities.

PBC dates back to the second half of the 1970s and was developed by the US Department of air force defense (Ozbek 2004; Ozbek and De la Garza 2013). Throughout 20 years of struggling, the Office of Federal Procurement Policy issued several pamphlets, guides, and best practices for PBC (OFPP 1998). Based on these efforts, many municipalities in the US started to convert their contracts to PBC under a pilot project. These municipalities were pleased with the maintenance contractors' performance, where they reported an average of 15% reduction in the contract price and 18% improvement in the roads' quality levels. In addition, Zietlow (2004) declared that a cost reduction between 10% and 20% took place in Australia, United States, and New Zealand after the application of PBC. Table **2-5** shows the cost savings of the PBC over the conventional contracts in different countries (Stankevich *et al.* 2009).

Table 2-5: *PBC cost savings over conventional contracts (Stankevich et al. 2009)*

Country Cost savings, %	Cost Savings (%)
Norway About 20-40%	About 20% - 40%
Sweden	About 30%
Finland	About 30% - 35%; about 50% less cost/km
Holland	About 30% - 40%
Estonia	20% - 40%
England	10% minimum
Australia	10% - 40%
New Zealand	20% - 30%
USA	10% - 15%
Ontario, Canada	About 10%
Alberta, Canada	About 20%
British Columbia, Canada	Some of might be in the order of 10%

Two of the most important decisions that should be carefully taken into consideration by the municipalities are the determination of the contract period and the length of the pilot project. For instance, Zietlow (2004) claimed that Guatemala and Honduras executed a two-year PBC for road maintenance by in-house staff with KPIs related to the routine maintenance only. In addition, it is necessary to consider it from both legal and financial perspectives. For instance, Latin America has a legal regulation that limits the contract period to a maximum of five years. As a result, to extend the contractual period, the laws must be changed (Zietlow 2004). Inspection is another issue for PBC, such that municipalities are not able to frequently and completely monitor and assess the performance of the maintenance contractor due to the limited financial resources. Thus, De la Garza *et al.* (2008) introduced a sampling procedure for evaluating the maintenance contractors' performance on roads. Additionally, Sultana *et al.* (2012) introduced seven main factors that should be considered by municipalities prior to applying PBC. The first issue is the municipality's obligation to define the performance specifications and set-up a standard for these performance measures. Then, the municipality should check the capability of the private sector to handle the road maintenance and reach the desired LOS quality. After that, the implementation stage takes place and an initial project is selected. A detailed risk analysis must be carried out to define the events that are out of the maintenance contractors' control and accordingly share those risks with the maintenance contractor. Hence after, the performance monitoring process takes place, where the maintenance contractor is evaluated according to their performance within the contract period. To assess the maintenance contractors' performance, De la Garza *et al.* (2009) hosted the five components for monitoring PBC and their direct relationship with the overall performance. Those components are: (1) LOS effectiveness that indicates the extent to which the contractual performance criteria and targets are met by the maintenance contractor across the contract period; (2) timeliness of response that evaluates the response time of the maintenance contractor to service requests related to events or deficient elements in the roadway that need to be attended to in a timely manner; (3) safety procedures that checks the maintenance contractor compliance with the safety standards. It also ensures that the road users, as well as the maintenance crew, are performing the work with no/minimal accidents and risk exposure; (4) quality of service that evaluates the customer perceptions with respect to the condition of the assets and maintenance contractors' performance; and (5) cost efficiency that assesses the cost savings accrued by the government because of engaging a maintenance contractor to perform the road maintenance services. Another issue that needs to be accounted for is the municipality's workforce (employees). The municipality's workforce will drastically decline after adopting PBC. For instance, 63% of the national road network is under PBC in Estonia and thus, the national workforce of the municipality declined from 2,046 employees in 1999 to 692 employees in 2003. Thus, municipalities should gradually account for this decrease through transferring their workforce to the maintenance contractors. Municipalities are moving from the conventional type of contracting to long-term PBC with an objective of decreasing their own risks and increasing the risks on the maintenance contractors (Queiroz 1999). Figure **2-3** shows the risk distribution among the different contractual approaches.

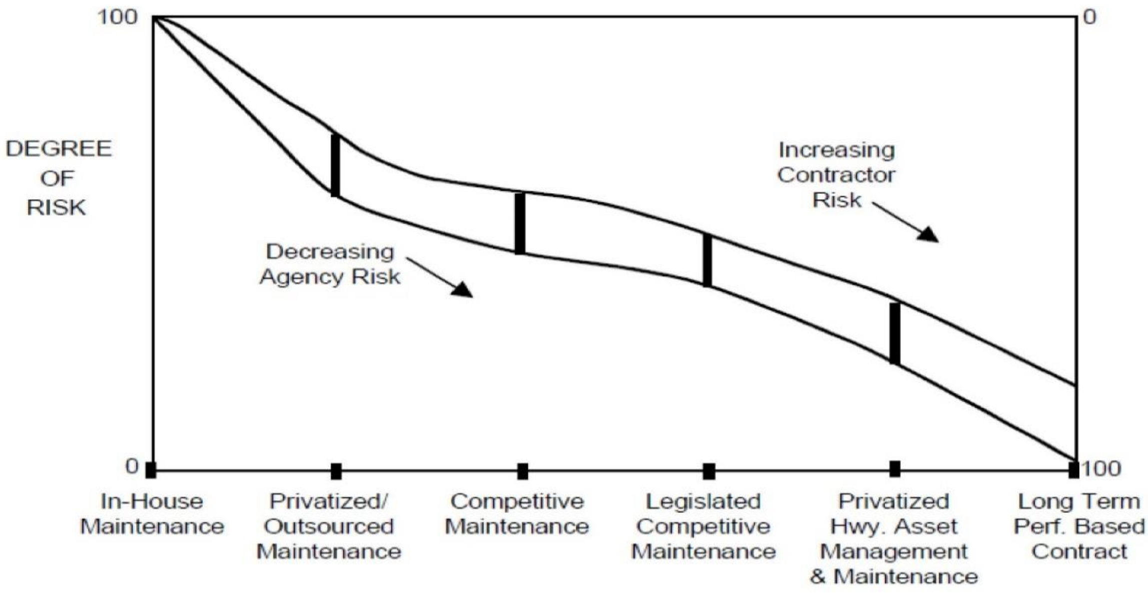


Figure 2-3: *Risk distribution with different contract approaches (Haas et al. 2001)*

The successful implementation of PBC is prerequisite on both properly-defined KPIs and adequately placed P/I system (Ganjidoost *et al.* 2017). The KPIs aim at accurately evaluating and assessing the service quality level performed by the maintenance contractor. Thus, those indicators should be Specific, Measurable, Achievable, Realistic, and Timely to schedule (SMART). Furthermore, Abu-Samra *et al.* (2018a) identified some rules for properly identifying the KPIs of roads and water networks. Moreover, the P/I system should be not only appealing in terms of encouraging the maintenance contractors to maintain the asset and improve its quality level to get the contractual incentives, but also strict in case the minimally acceptable service quality levels were not met. The P/I could be either monetary or non-monetary (i.e. extension or contraction of the contract duration). Throughout the last decade, it has been noticed that municipalities are lacking proper control over the maintenance contractors through poorly-defined KPIs, inadequate incentives, and high penalties. The tendency to place high penalties associated with low incentives indirectly forces the maintenance contractors to significantly increase their cost contingencies to cover any risks they might encounter across the contractual period.

2.4.2 *Discussion and Analysis*

Numerous scholars suggested that PBC could be a solution to fix the municipal financing issues (VFM 2016; Pour *et al.* 2016; Alm 2015; Tassonyi and Conger 2015; FCM 2012; Kitchen 2006). Other scholars focused on the PBC aspects such as; contract duration, pay factors, P/I, performance indicators (Buddhavarapu *et al.* 2016; Alyami *et al.* 2017a; 2017b; 2015; Alymai and Tighe 2017a; 2017b; 2016; 2015; 2013; Liu *et al.* 2016; Schoenmaker and Bruijn 2016; Rajan *et al.* 2010; Haas *et al.* 2009; VFM 2016; Selviaridis and Wynstra 2015; Soliño 2015; Buiten and Hurtmann 2015; Olander 2014; Grant *et al.* 2013; Lammam *et al.* 2013; Sultana *et al.* 2013; Hensher and Houghton 2004). For instance, Pinero and De la Garza (2003) stated that PBC calls for performance-based work, in which the outcomes, represented through KPIs, are specified rather than the material or method of implementation. Furthermore, the study stated that this contracting scheme could act as an excellent tool for improving government expenditures while maintaining the assets' condition. On the other hand, they stressed on the necessity of properly identifying the KPIs as well as the resistance to change issue. Tomanelli (2003) argued that PBC is better than conventional maintenance contracting because the maintenance contractors are aware of cheaper and better processes to achieve the desired outcomes in a more efficient manner. Furthermore, they indicated that the competitiveness between the maintenance contractors motivates them to submit the least financial offer. Ozbek (2008) declared that, in some cases, the maintenance contractors' innovations in the materials or processes could bring some undesirable consequences to the project in terms of contractual KPIs. Furthermore, the responsibility of the unperformed work or defects at the end of the contract should be clearly defined in the PBC to avoid any vague clauses that could potentially cause conflicts. Ozbek (2004) discussed the PBC from a contractual perspective. The study developed the main performance warranties for PBC to reduce the risk on the municipalities and improve the performance of the PBC. The outcome of implementing those performance warranties could be summarized in the following points: (1) allows the maintenance contractor to deliver the project using their own best practices, as they are obliged to meet certain KPIs regardless the method; (2) maximizes the maintenance contractors' innovation as the maintenance contractors' may get incentives in case of promoting any innovation throughout the contract. In addition, this may give the municipalities the opportunity to learn these new technologies and apply them to their in-house projects; (3) risk is fully transferred to the party having much control over the project (maintenance contractor). As a result, the POF is minimized as the maintenance contractor will be implementing innovative methods to achieve the pre-defined contractual KPIs; (4) cost-effective for both parties involved in the contract. There will be a high probability of attaining cost savings while reaching the desired KPIs, enhancing the network condition, and transferring the risk to the maintenance contractor. In addition, the maintenance contractor will save money through optimizing the utilization of the expenditures and minimizing the LCC while meeting the contractual KPIs; (5) builds a long-term, trustworthy, and stable relationship between the municipalities and the maintenance contractor, creating an opportunity for future work between both parties; (6) minimizes the negative impact of the infrastructure projects on the public as the municipalities tend to define strict KPIs on the maintenance contractor to reduce the service disruption duration, resulting in shorter driving times through and around work zones and thus, enhancing the public safety. In addition, it reduces the negative impacts of noise and pollution because of the reduced disruption duration introduced as a separate KPI in the contract (Carpenter *et al.* 2003); (7) minimizes the inspection frequency as there are certain KPIs defined in the contract to evaluate the maintenance contractors' performance. On the other hand, the quality control is the maintenance contractors' responsibility, which releases the municipality from allocating both financial and technical resources for the quality control; (8) improves the condition and LOS of the asset due to the timely and effective maintenance activities; and (9) minimizes the administrative costs needed for bidding, administrating, and managing numerous short-term individual contracts. After applying PBC, the municipality will be dealing with a single contract instead of several short-term contracts with the sub-contractors.

2.4.3 *Main Findings and Limitations*

Even though several scholars studied PBC for roads and transportation projects (Alsharqawi *et al.* 2017; Abu-Samra *et al.* 2017d; Rashedi and Hegazy 2016a, 2016b; 2016c; Abu-Samra 2015; Kassab *et al.* 2011; Roelich *et al.* 2015; FCM 2012; Kassab *et al.* 2007), few applied PBC on other corridor municipal infrastructure assets such as; water and sewer networks (PPPIRC 2007; FBC 2013; OCED 2011; Fanner 2006). Furthermore, PBC research focused on the contractual and risk management aspects, with very limited focus on integrating the contractual KPIs performance and P/I system with the decision-support system, which links the KPIs' performance with their associated thresholds and P/I. This missing link is the core for taking informed maintenance and rehabilitation decisions across the contract duration and assets' life-cycle accordingly. In that context, the key limitations could be summarized as follows:

1. Absence of PBC contracts for water and sewer networks;
2. Missing link between the KPIs' performance and their associated thresholds and P/I;
3. Absence of integrated contractual -based decision-support system for managing the municipal infrastructure;
4. Lack of properly defined KPIs' thresholds to ensure proper risk allocation and lower contingency; and
5. Lack of well-defined P/I to incentivize the contractors to meet the pre-set KPIs' thresholds and gain extra profit. Furthermore, strict penalties should be defined to ensure contractors are obliged to meet minimal LOS thresholds.

PBC has been globally applied in many nations and it showed to be cost-effective for the municipalities as it displayed fair amount of financial and administrative savings. A summary of the benefits could be condensed in the following points:

1. Partially transfers the risk of non-compliance with the service quality standards to the maintenance contractor. Figure **2-4** shows the risk distribution of the road maintenance activity beginning with the in-house maintenance and ending with the long-term road concessions;

2. Reduces the overall maintenance cost through the economy of scale. In addition, it secured long-term funding for maintenance programs;
3. Introduces the concept of performance risk sharing through the contractual P/I system;
4. Expands the role of the private sector by introducing a new area of work, where road maintenance was always the role of the public sector. This created an opportunity for maintenance contractors to efficiently plan their work to both meet the agreed service quality measures and increase their profit margins;
5. Increases the efficiency and effectiveness of road maintenance operations with the employer having the upper hand opportunity through properly-defined KPIs; and
6. Provides the municipalities with a better budget certainty, as the monthly maintenance expenses are pre-defined in the contract.

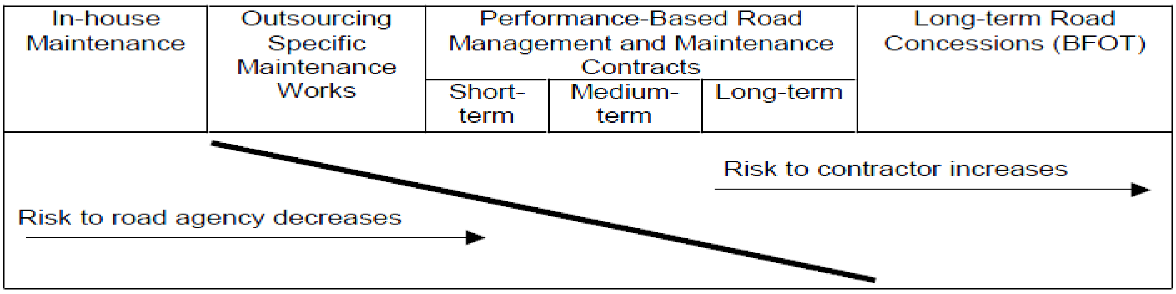


Figure 2-4: *Road maintenance risk distribution in different contract forms (Zietlow 2004)*

2.5 Integrated Asset Management: Discussion and Analysis

Coordination of intervention activities has been thoroughly considered as a part of the wider notion of the dependency and interdependency relationships among infrastructure systems. The dependency between the systems refers to a unidirectional relationship, such that one system relies on the other whereas interdependency refers to the bi-directional relationship among the infrastructure systems (Rinaldi *et al.* 2001). It could be classified to functional and spatial depending on the operational dependency and the proximity between systems respectively (Zimmerman 2010; Thacker *et al.* 2017; Chou and Tseng 2010). However, Rinalidi *et al.* (2001) classified the infrastructure interdependency to four categories: physical; cyber; geographical; and logical. Multiple computational approaches have been used such as; simulation, econometrics, network-based analysis, system-of-system modeling. Ouyang (2014) has conducted an extensive state-of-the-art review to summarize the interdependency modeling approaches. Those approaches could be categorized to (1) simulation based approaches such as; agent-based simulation, continuous simulation, and system dynamics

(Macal and North 2002); (2) econometric approach such as; input-output models (Haimes and Jiang 2001; Santos and Haimes 2004); (3) network analysis approach such as; advanced geospatial analysis, hydraulic network modeling, and geometric proximity analysis (Islam and Moselhi 2012; Jeong *et al.* 2006; Duenas-Osorio *et al.* 2007); and (4) system-of-system approach such as; integrated Systems-of-System (SoS) modeling and High Level Architecture (HLA) simulation, and integrated generalized transportation network and system of systems (Eusgeld *et al.* 2011; Friesz *et al.* 2001). Even though numerous scholars have extensively studied the infrastructure interdependency within the operational phase, focusing particularly on how the system disruption propagates through related networks, sparse attention has been given to the interdependency occurring while undertaking the interventions (i.e. repair, rehabilitation, and replacement) in terms of geographical and temporal dimensions. Moreover, even though the temporal dimension has a direct impact on the spatial, physical, and financial dimensions, it has not been thoroughly studied.

Throughout previous decades, several scholars developed innovative funding and prioritization approaches for asset management. The relationship among numerous factors affecting the assets' performance, deterioration processes, and service/physical failures are neither linear nor systematic. Consequently, the integrated planning, fund allocation, and prioritization of intervention projects across multiple co-located assets' life-cycles are complex and challenging. To overcome such complexity, different prioritization techniques and approaches were investigated through different sets of operational, physical, and environmental factors. The different multi-criteria decision-making has different knowledge/expertise requirements, which requires using different approaches to assign criteria values and combine their scores. However, most of them assign values to the alternatives of each criterion and multiply them by their corresponding weights to get a final score (Huang *et al.* 2011). Within the multi-criteria decision-making domain, various scholars prioritized the life-cycle funding by estimating the assets failure using either, hierarchical models such as; AHP (Al-Barqawi and Zayed 2006b; Shahata and Zayed 2016; Sharma *et al.* 2008), or network models such as; ANP (Al-Barqawi and Zayed 2006a). AHP and ANP focus on modeling the knowledge of a group of experts to drive the relative weights of the factors and sub-factors on the overall impact. Scholars categorized each set of criteria under a specific factor, which is chosen by the domain experts. For example, Al-Barqawi and Zayed (2008) categorized the deterioration factors into physical, operational, and environmental. Combining the different sets of criteria under the relevant factors leads to a structured decision model. Fares and Zayed (2009) integrated sixteen pre-failure and post-failure consequences of failure factors into a risk-based prioritization model. The models could be crisp or fuzzy and are commonly integrated with MAUT. Data ambiguity is commonly modeled through fuzzy logic. For the deterioration and failure models, scholars categorized them into: (1) statistical and mathematical survival models such as; Weibull model, to predict either the assets POF and/or the network reliability (Abu-Samra *et al.* 2017a; 2017b; 2017c); and (2) data-driven approaches that use historical maintenance records to either: (a) build empirical deterioration model using techniques such as; regression models (Kimutai et al. 2015; Abu-Samra *et al.* 2017a; b; c); or (b) use model-free methods such as; ANN to drive internal relationships among decision factors and their impact(s) (Al-Barqawi and Zayed 2006a; 2008; Bakry *et al.* 2016). Other scholars used simulation models to support the decision-making, in case of the presence of historical data (Shahata and Zayed 2010a; 2013; Francisque *et al.* 2011; Sadiq *et al.* 2014; Gharaibeh *et al.* 2006; Ganjidoost *et al.* 2015; Dueñas-Osorio *et al.* 2007; Scaparra and Church 2008; Roelich *et al.* 2015; Goodall *et al.* 2015; Too and Too 2010; Hansen and Neale 2014).

To evaluate the alternative investment options more effectively, some scholars utilized spatial modeling to coordinate the corridor municipal interventions using GIS and dynamic neighborhood methodology (Osman and El-Diraby 2006; Kielhauser *et al.* 2017; Halfawy *et al.* 2002; 2000). Other scholars utilized LCC analysis, considering all direct and indirect cost categories such as; direct planning, design, acquisition, maintenance, ownership, operation of the asset (Ammar *et al.* 2012b; Farran and Zayed 2012; Moselhi *et al.* 2009; Faust *et al.* 2015; 2013; Matthews *et al.* 2011). For instance, Kleiner *et al.* (2001) used dynamic programming to calculate the LCC for the rehabilitation projects. Moreover, Ismaeel and Zayed (2018) developed a budget allocation model using fuzzy approach for water mains. The use of LCC techniques increased the possibility of cost-effectiveness and savings (Moselhi *et al.* 2009; 2005). The LCC modeling approaches could be either deterministic, where the decisions are commonly made based on the net present value of the intervention alternatives; or probabilistic, where different costs are associated with relevant probabilities (Shahata and Zayed 2013; Oh *et al.* 2011; Michele and Daniela 2011; Lambert *et al.* 2012; Karvetski *et al.* 2009; Elbeltagi and Tantawy 2008).

Due to the increasing infrastructure deficits, extra challenges were added to the decision-making process such as; optimal utilization of the limited budgets, prioritization of municipal projects, enhancement of the network performance, reduction of service failure and disruption risks, etc. Furthermore, planning and execution of the corridor infrastructure intervention projects have detrimental social, economic, and environmental impacts on the society. Consequently, asset managers are continuously seeking efficient, effective, and near-optimal approaches that maximize the decisions' benefits and savings and minimize the losses and LCC. Accordingly, it is a multi-objective optimization problem by nature, due to the existence of multiple conflicting objectives. According to Marler and Arora (2004), "*there is no single global solution to a multi-objective problem*". Multi-objective optimization can reach a whole set of pareto near-optimal solutions in one optimization run, which will require several runs to obtain the same level of information in the case of single-objective. According to Zeleny (1982; 2011), maximizing a single-criterion is not a real optimization process. Using a single-objective optimization, the decision-maker must express some preferences in advance such as; the goals' order or priority (i.e. maximize performance, then use it as a constraint in the second run to optimize another decision-indicator such as; LCC, and so on). Preferences include assigning relative weights of importance. However, using a multi-objective optimization approach, one expresses preferences after running the model (Savic 2002; Hutto 2016). The user can investigate several scenarios using different relative weights after running the optimization engine. Scholars utilized goal optimization to trade-off multiple competing objectives such as; LCC, risk, LOS, user-costs, and economic losses (Osman 2015; Abu-Samra *et al.* 2018a) through combining all the weighted deviations from the thresholds along with their relative weights, forming an overall deviational goal.

The applications of multi-objective optimization within the domain of infrastructure asset management has received considerable attention from researchers. For instance, Rashedi and Hegazy (2014) compared segmented GAs and exact numerical optimization methods (GAMS/CPLEX) in the capital renewal planning of large infrastructure systems and came up with a conclusion that numerical methods are more superior. Furthermore, numerous scholars studied multi-objective techniques including; linear programming, and integer programming. For instance, De la Garza *et al.* (2011) selected the optimal pavement intervention plan at a network level. In addition, Hegazy and Elhakeem (2011) designed a framework for solving large-scale combinatorial bi-level optimization problems that include discrete, integer, and two-level decisions. The framework was applied to the buildings sector to select the optimal repair timing for various building components.

Abu-Samra *et al.* (2018a) developed a multi-objective optimization model for the corridor infrastructure. To overcome the huge search space issue, the model utilized a phased-network approach, where the project level decisions were taken separately for each asset and then the results were used as an input for the network level trade-off analysis. The system used integrated goal optimization, dynamic programming, integer programming, and GAs to prioritize the corridors for renewal/rehabilitation/preventive maintenance across the planning horizon while respecting the pre-set performance thresholds and the available annual budget. Goal optimization was used to model the conflicting objectives via a percentile ranking approach. Dynamic programming was used to overcome the extended planning horizon issue and riven the planning horizon into smaller ones with five-years segmentation. Bi-level dimensional integer programming was used to model the project and network level decision variables. Similarly, Abu-Samra *et al.* (2017a) developed a preemptive goal optimization-based multi-objective model for the municipal co-located infrastructure. The system used preemptive goal optimization to fragment the multi-objective problem into single objective ones, based on the objectives ranking. Once the desired objective outcome is reached, the system automatically turns to the 2nd one while respecting the 1st objective outcome and placing it as a constraint. Other scholars developed integrated non-preemptive goal optimization and GAs models for corridor infrastructure to minimize the financial, temporal, and performance deviations from the pre-set budget, resources, and performance threshold respectively (Abu-Samra *et al.* 2018a; Osman 2015). Likewise, scholars developed bi-level goal optimization model for transportation networks using penalty and compromise methods to minimize the financial and performance deviations. The developed model was formulated in GAMS modeling environment using CPLEX solver. The penalty method uses the weighted sum technique to combine multiple objectives into a single function after assigning different weights of importance for each objective to create a set of pareto-optimal solutions. However, the compromise method is founded on the ε-constraint technique, which relies on maximizing/minimizing one of the objectives and setting the remaining objectives as constraints (Frangopol and Liu 2007; Mavrotas 2009). Yet, those remaining objectives are mathematically formulated in the form of equalities, where they should meet certain limits that are identified by separately running individual optimization for each objective to determine the most efficient value (Saad *et al.* 2017; 2016; Colson *et al.* 2007).

Saad and Hegazy (2017a) developed an enhanced benefit-cost analysis optimization method to achieve an equilibrium state at which fair and equitable allocations are made among all the co-located asset categories. The study used CPLEX solver to maximize the network benefit-cost ratio. Yet, the study used deterministic deterioration and it was only applied on the roads and bridges. Likewise, Saad and Hegazy (2017b) developed a microeconomic-based heuristic model to optimize the expenditures' efficiency over different building components. Yet, the study did not account for the uncertainties associated with the deterioration of the building components as well as their associated costs. El-Anwar *et al.* (2016a; 2016b) developed mixed integer-linear programming and pareto optimization model for scheduling the post-disaster reconstruction plans for transportation networks. The study aimed at minimizing the network recovery time and public expenditures while prioritizing the post-disaster reconstruction projects. Yet, the study only dealt with extreme disastrous events (i.e. hurricanes, earthquakes, and tsunamis) and did not account for the typical aging deterioration. CGI (2015) discussed the importance of utilizing a holistic asset management approach and highlighted the role of optimization in acquiring balanced decisions that consider costs, risks, opportunities, and performance. Elsawah *et al.* (2016) developed a decision-support system with a dynamic weighting system for prioritizing the repair of the water and sewer networks. The study relied on the Risk Index (RI), represented through the POF and COF, to prioritize the repair of the water and sewer pipes. Yet, the study did not consider the LCC while prioritizing the repair of the water and sewer pipes. Shahata and Zayed (2016) established an integrated risk-assessment framework for municipal infrastructure to facilitate the decision-making process while planning the corridor rehabilitation projects. The study relied on the risk to prioritize the rehabilitation of the corridors using mixed-delphi and AHP with unsupervised K-means clustering. Furthermore, the study proposed cost-effective risk mitigation measures for each risk category. Yet, the study did not consider the LCC in the decision-making process and assumed equal weights of importance to the POF and COF.

While many scholars investigated multi-objective optimization to model one municipal network such as; water or road, few scholars attempted to use it for integrating two or more networks. Integrated asset management is still relatively limited in literature, especially, the ones with multi-objective optimization. For instance, Osman (2015) developed a framework for temporal coordination of co-located infrastructure systems taking the financial, risk, and LOS triggers into consideration while planning the interventions of the corridors. The trade-off between delaying and bringing forward the intervention activities has been conducted using goal optimization approach based on the pre-defined thresholds of the goal constraints. Similarly, Tscheikner-Gratl *et al.* (2015) developed a strategic asset management approach that prioritizes the street sections and the underlying infrastructure (i.e. sewer and water supply networks) for rehabilitation. The study developed a priority model that accounts for the deterioration of the pipes in terms of discharge water in water supply networks and the urban flooding in sewer networks. Moreover, Carey *et al.* (2013) developed an asset management plan for the municipal right-of-way infrastructure networks while considering the economic outcome and monetary savings. Atef and Moselhi (2014) used the local spatial vulnerability of failure to assign priorities. Other approaches were developed for integrating the varying municipality perspectives (Rashedi and Hegazy 2014; Khan *et al.* 2015), or integrating multi-components within the same network or among two networks such as; sewer and wastewater (Khan *et al.* 2011; Azeez *et al.* 2013), water and wastewater (Francisque *et al.* 2011; Sadiq *et al.* 2014).

2.5.1 *Main Findings and Limitations*

Even though previous scholars developed asset management frameworks and models, there were some limitations in numerous aspects that could be summarized as follows:

1. Failure to account for the propagation of the systems' disruption given the spatial interdependency among the co-located infrastructure systems;
2. Lack of holistic-based interventions' planning for the co-located infrastructure systems, such that most scholars independently planned the assets' interventions, based on their condition state only, neglecting the condition of the co-located assets;
3. The dimension of "time" was not always considered in the decision-making process, such that scholars developed prioritization frameworks that ranks the assets for intervention based on their current condition only, without forecasting their future condition state;
4. Absence of an integrated contractual and asset management system that links the KPIs' performance and the P/I application with the decision-making process.

2.6 Research Gaps

In spite the fact that plentiful modeling approaches have been utilized in the last decade, some limitations have been noticed as follows: (1) propagation of the system disruption has not been appropriately considered as vast majority of the research was focusing on the operation phase; (2) the dimension of "Time" was not considered as a key aspect that influence the intervention decisions; (3) lack of focus on holistic-based intervention for interdependent co-located infrastructure systems (i.e. roads, water and sewer); and (4) absence of integrated contractual and asset management system. The exerted efforts have been directed towards developing decision-support systems on a single-asset level. However, there is a paucity of literature on the integrated asset management in the wider notion of optimization and decision-making. Several scholars have developed single-objective optimization models for integrated asset management. However, few scholars developed dynamic multi-objective optimization models that incorporate the conflicting perspectives and plans the corridor interventions accordingly. Although PBC has been widely recognized as a potential solution for transferring the operational risks to the private sector while maintaining higher levels of service for the assets under study, scholars failed to develop integrated contractual and asset management models that aids both municipalities and maintenance contractors in setting up their performance thresholds, P/I system, and maintenance plans. Moreover, it was only applied to roads and transportation projects, with few applications on the water and sewer rehabilitation projects. Therefore, this study aims at developing an integrated performance-based multi-objective asset management system for the corridor infrastructure. The system accounts for the contractual performance indicators while selecting the optimal intervention plan for the corridor infrastructure. Furthermore, it considers the P/I in the financial computations to provide the maintenance contractors with a rough estimate on the LCC associated with the corridor infrastructure intervention.

3 CHAPTER 3 – RESEARCH METHODOLOGY

This chapter opts at proposing a novel methodology for integrating the municipal infrastructure intervention actions from both contractual and asset management perspectives. The chapter revolves through five key aspects as follows: (1) KPIs' selection criteria that identifies the criteria used to select the contractual performance indicators; (2) PBC-based contractual scheme that proposes an integrated consortium internally among the departments, joint venture contract among the maintenance contractors, and PBC between the municipal consortium and the maintenance contractors' joint venture; (3) multi-dimensional performance assessment models that assess the coordination benefits over the conventional approach; (4) optimization models that formulate the pre-contract and post-contract scenarios; and (5) PBC-based asset management system that combines the developed models to aid asset managers in taking informed intervention decisions.

3.1 Main Research Framework

This research proposes a detailed multi-objective framework for corridor infrastructure under PBC. The research methodology rests on three core foundations as follows: (1) integrated PBC contractual scheme; (2) multi-dimensional assessment models; and (3) multi-objective optimization for PBC-based asset management. It spins around five main phases, as shown in Figure 3.1. The 1st phase is investigating the literature review with an objective of gathering information about various aspects such as; optimization for asset management; municipal contractual practices; and asset management. The main outcomes of this phase are: (1) defining the municipal corridor infrastructure interdependencies and the current asset management contractual practices; and (2) identifying the multi-objective optimization techniques and the coordination dimensions along with their assessment criteria. Hence after, the 2nd phase is centered on the PBC parameters, which aims at analyzing the different factors that affect the PBC from both owners (i.e. municipalities) and maintenance contractors' perspectives. In this phase, the KPIs will be defined along with their deterioration patterns, inspection frequencies, and degrees of importance for being inputted to the multi-objective optimization model. The 3rd phase is the technical foundation of this research, where a novel integrated PBC contractual scheme will be developed. The contractual scheme functions through a consortium between the municipal departments, a joint venture between the maintenance contractors, and a PBC between the municipal departments' consortium and maintenance contractors' joint venture.

To assess the novel contractual scheme, the 4th phase takes place to combine the outputs of the 2nd and 3rd phases and develop multi-dimensional performance assessment models that rest on eight dimensions: (1) spatial, (2) temporal, (3) financial, (4) physical, (5) risk, (6) resilience preparedness, (7) efficiency, and (8) effectiveness. Those dimensions are the PBC multi-objectives, in other words KPIs, as will be detailed later in this chapter. Finally, the 5th phase is building a PBC-based asset management system that functions through five main models as follows: (1) central database model that contains the data of the corridor infrastructure under study; (2) deterioration model that predicts the future condition state of each asset; (3) integrated LCC model that calculates the LCC of the systems, corridors (i.e. group of systems), and network (i.e. group of corridors); (4) multi-dimensional performance assessment models that compute the state of the pre-defined KPIs throughout the planning horizon; and (5) optimization models that function through several optimization engines and act as a decision-support system for both municipalities and maintenance contractors in pre-contract and post-contract phases as will be highlighted later in this chapter. Towards the end, the model will be applied to two case studies and the results will be plotted against the conventional scenario to visualize the coordination savings in terms of the pre-defined KPIs.

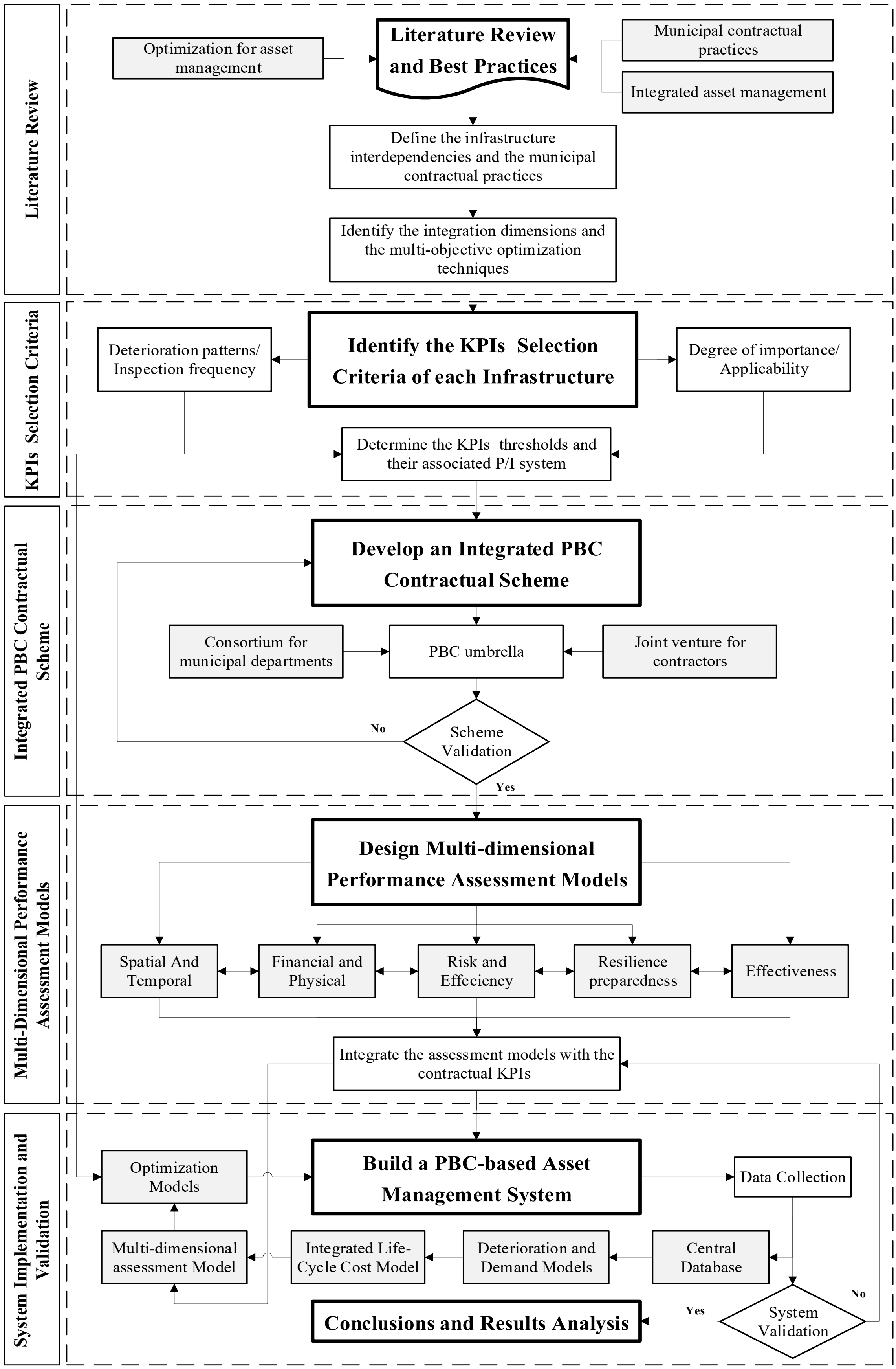


Figure 3.1: *Research framework*

3.2 Literature Review and Best Practices

The literature review investigated and analyzed three research areas to determine the best practices as detailed earlier in the previous chapter. The 1st research area was the optimization where different single and multi-objective optimization techniques and algorithms have been studied. Furthermore, an extensive review of the optimization applications in asset management was carried out. Accordingly, a novel optimization approach was developed to overcome the limitations imposed by the previous scholars' models. The novel optimization approach functions through an integrated percentile hierarchical goal optimization along with a GAs or MOSEK optimization engine, as will be detailed later in this chapter. The 2nd research area was the municipal contractual practices where various types of contracts (i.e. conventional interventions, consortium, joint venture, PPP, and PBC) were investigated and their limitations were identified and taken into consideration while developing the novel integrated PBC contractual scheme. The final research area was the integrated asset management where several aspects have been studied as follows: (1) dimensions and indicators, which are reflected in the KPIs as highlighted earlier in the previous chapter; (2) indicators' weights of importance that defines the KPIs' weights of importance; (3) integrated asset management intervention savings in terms of space, time, cost, condition, resilience preparedness, disruption, reliability, effectiveness, and efficiency; (4) socio-economic effects, which are converted to user costs resulting from the service disruption; and (5) corridor infrastructure interdependency, which is the main trigger behind thinking of interventions' coordination at the first glance. Infrastructure interdependency has been studied from a multitude of dimensions such as; spatial, cyber, physical, geographical, and logical. Accordingly, based on the analysis of those aspects, the research objectives were defined, and the methodology was developed.

3.3 Key Performance Indicators (KPIs') Selection Criteria

There is a need for careful KPIs' selection due to the multi-asset nature with different characteristics such as; deterioration rates, useful lives, installation years, intervention costs, and physical condition implications. Thus, the comparison criteria should be unified among the assets to assess their performance throughout the planning horizon and accordingly take informed intervention decisions. Moreover, the established KPIs need to be indicative and SMART to predict their annual performance from economic, financial, physical, and social perspectives, before and after applying different intervention plans. Accordingly, after conducting an exhaustive literature review, a set of categories and rules were set to define the KPIs as detailed in Table 3-1. Based on those rules, the KPIs were categorized into the following: (1) financial, (2) temporal, (3) spatial, (4) physical, (5) risk, (6) resilience preparedness; (7) intervention efficiency, and (8) intervention effectiveness. Those indicators were precisely chosen to account for the multi-asset nature and consider the different stakeholders' preferences. The temporal category represents the time needed to undertake an intervention or the service disruption duration. The outcome of the temporal category feeds both the spatial and financial categories. The financial category represents the impact of decreasing ownership costs and increasing operating and maintenance costs of the asset. It computes the LCC including all the direct and indirect costs associated with undertaking an intervention or service disruption (i.e. rehabilitation, user costs, replacement, etc.). The disruption/intervention duration and spatial extent are utilized to compute the indirect costs within the financial category. The spatio-temporal category computes the disruption/intervention area for the different intervention scenarios. The outcome of the temporal category, represented through the disruption/intervention duration, was utilized in the spatio-temporal model as the spatial extent was not enough to represent the savings. The physical category represents the corridor condition state, which is necessary for taking timely intervention decisions. The physical category includes future prediction models for the right-of-way corridor assets to compute the physical performance of the assets and take prompt corrective actions. The condition of the asset is represented as a percentage, such that "0%" represents an asset in a failing condition whereas "100%" represents an asset in an excellent condition. The risk category represents the probability and consequences of failure for any assets within the corridor. It represents the corridors, including all the right-of-way assets, with a risk index to assist asset managers in their decision-making process. The resilience preparedness category represents the preparedness of the asset to adapt with demand changes taking place due to the urbanization (i.e. population growth, land use change) and climate change (i.e. increased rainfall intensity and frequency). The resilience preparedness of the asset is represented by a percentage between the demand and supply, such that the demand is computed from an urban hydrological model whereas the supply is simply based on the pipe diameter and the capacity of the water supply station or wastewater treatment plant, depending on the asset under investigation. For instance, a ratio of "90%" implies that the current supply is barely meeting the demand, which indicates the need to replace the existing pipes in the near future with larger diameters to meet the demand. However, a ratio of "110%" implies that the demand exceeds the supply, which is troublesome in both sewer or stormwater systems and even more complicated in the combined sewer and stormwater systems because of the overflooding that will occur around the pipes' surrounding areas. The intervention efficiency category represents the performance of the intervention plan in terms of resources' utilization. Thus, it reflects the percentage of time consumed to undertake the intervention activities over the total disruption period to restore all the right-of-way assets. Finally, the intervention effectiveness represents the quality/performance of the intervention. In simpler terms, it reflects the amount of operating time expected until the next major intervention, without undertaking any disruptive intervention activities after the intervention program is accomplished. Table 3-2 summarizes the KPIs' categories along with their performance measures and their associated description and ranges.

Table 3-1: *KPIs' rules (Abu-Samra et al. 2018a)*

Indicator Category	Indicative Rules
Accuracy	- The indicator should consider the precision level needed while measuring. - The indicator should consider the difficulty level, represented either by the frequency or easiness of measurement.
Frequency	- The indicator should frequently (i.e. annually) track the assets' performance throughout the planning horizon. - The indicator's rate of change shall be highly-considered (i.e. the KPI should experience a periodical difference in the asset state).
Financial	- The indicator should consider the costs needed for frequently measuring and controlling the asset.
Ownership	- The indicator should have an owner, who is held liable/responsible for.
Portability	- The indicator should fit multi-assets with different features and attributes such as; deterioration rates, useful lives, construction years.
Subjectivity	- The indicator should be objective-oriented and should include a pre-defined set of rules for measuring an asset attribute to guarantee a consensus agreement among different parties.

Indicator Category	Indicative Rules
Understandability	- The indicator should consider the easiness of understanding and tracing the triggers behind a sudden rise/fall throughout the assets' life-cycle.

Table 3-2: *KPIs' categories and performance measures*

Performance measure	KPI	Description	Value/Range
Financial	LIF	Potential cost savings that can be attained due to integrating common activities while undertaking the intervention	No savings: LIF=1 Savings possible: LIF>1
Temporal	NCR	Potential time savings that can be attained due to integrating common and parallel activities while undertaking the intervention	No savings: NCR=1 Savings possible: NCR>1
Spatial	STIF	Time and space savings that can be attained while undertaking a fully-coordinated intervention as opposed to several conventional interventions	No savings: STIF=1 Savings possible: STIF>1
Physical	CIF	Condition improvement due to undertaking fully-coordinated intervention as opposed to several conventional interventions	No savings: CIF=1 Improvement possible: CIF<1
Risk	RIF	Risk improvement due to undertaking fully-coordinated intervention as opposed to several conventional interventions	No savings: RIF=1 Improvement possible: RIF>1
Resilience Preparedness	RPIF	Resilience preparedness improvement due to expanding the network capacity to meet the increasing demand	No savings: RPIF=1 Improvement possible: RPIF>1
Efficiency	IEF	Proxy for the nuisance caused by repeated interventions executed for the same corridor within a short time span	Highest efficiency: IEF=1 Lower efficiency: IEF<1

Performance measure	KPI	Description	Value/Range
Effectiveness	IFF	Proxy of time without any disruption once the intervention program is completed	Higher effectiveness: IFF<< Lower effectiveness: IFF>>

3.4 Integrated Performance-based Contracts (PBC) Contractual Scheme

The integrated PBC contractual scheme revolves through three contractual models to fit the multi-asset nature and guarantee proper risk allocation among the involved parties. In this case, the involved parties are divided into two categories: (1) municipal departments, and (2) maintenance contractors. Due to the huge differences among the corridor infrastructure assets (i.e. service life, deterioration pattern, management scale, LOS, construction/intervention methods, etc.), each category hires their own specialists for each asset, such that the municipalities have different departments that manage each asset separately. Furthermore, there rarely exists a maintenance contractor who is specialized in repairing/rehabilitating multiple assets. However, given the fact that the corridor assets are spatially interdependent such that a failure of an asset may affect the service of another one, intervention decisions shall not be solely taken. Thus, consortium, joint venture, and PBC were integrated, as shown in Figure 3.2, to guide the relation among the municipal departments, maintenance contractors, and municipal departments with the maintenance contractors respectively. The first contractual model was the "consortium model among the municipal departments", as shown in Figure 3.3. A consortium agreement is "*Reciprocal arrangement in which the members of a group of firms undertake to help each other in case of an emergency, such as; sharing their facilities with a member who suffers a disaster or is under a threat.*" (Business dictionary 2015). Some cities took actions and drafted an inter-municipal agreement to guide the relationship and ensure smooth collaboration in terms of data sharing and intervention planning among the municipal departments (Nova Scotia 2006; KPMG 2012). Thus, the consortium agreement among the municipal departments should take place to:

1. Define common PBC asset-based KPIs
2. Identify the asset-based LOS thresholds
3. Set the annual intervention budget
4. Specify the inspection frequency and techniques for assessing the KPIs'
5. Classify the assets interdependencies

6. Outline the KPIs and their associated P/I system
7. Determine the optimal contractual period

After completing this phase, the consortium should be able to draft a PBC that contains a set of KPIs along with thresholds, P/I system, and prequalification documents for the maintenance contractors. Hence after, the prequalification phase takes place to check the capability of the applicants (i.e. joint ventures) to handle the job, based on the prequalification criteria set earlier. Finally, the bidding process takes place and the joint venture with the highest score is awarded the contract, as detailed in Figure 3.3.

On the other hand, the maintenance contractors are bound together through a joint venture contract, which is "*a business entity created by two or more parties, generally characterized by shared ownership, shared returns and risks, and shared governance.*" (Roos *et al.* 2010). The objective of choosing the joint venture contractual model is that the risks and returns are shared among the parties, which guarantees more diligence for enhancing the cooperation to maximize the interventions' efficiency and share the profits and losses. As a result, the maintenance contractors will rely on asset management specialists as middle-level managers, who will be held responsible for a group of areas that divides their horizontal projects into corridors for better management, as shown in Figure 3.4. The asset management specialist will be focusing on meeting the pre-defined contractual KPIs (i.e. corridor LOS threshold). Furthermore, they will be responsible to schedule the interventions across the planning horizon to maximize the potential coordination savings in terms of space, time, cost, resilience preparedness, risk, reliability, efficiency, and effectiveness.

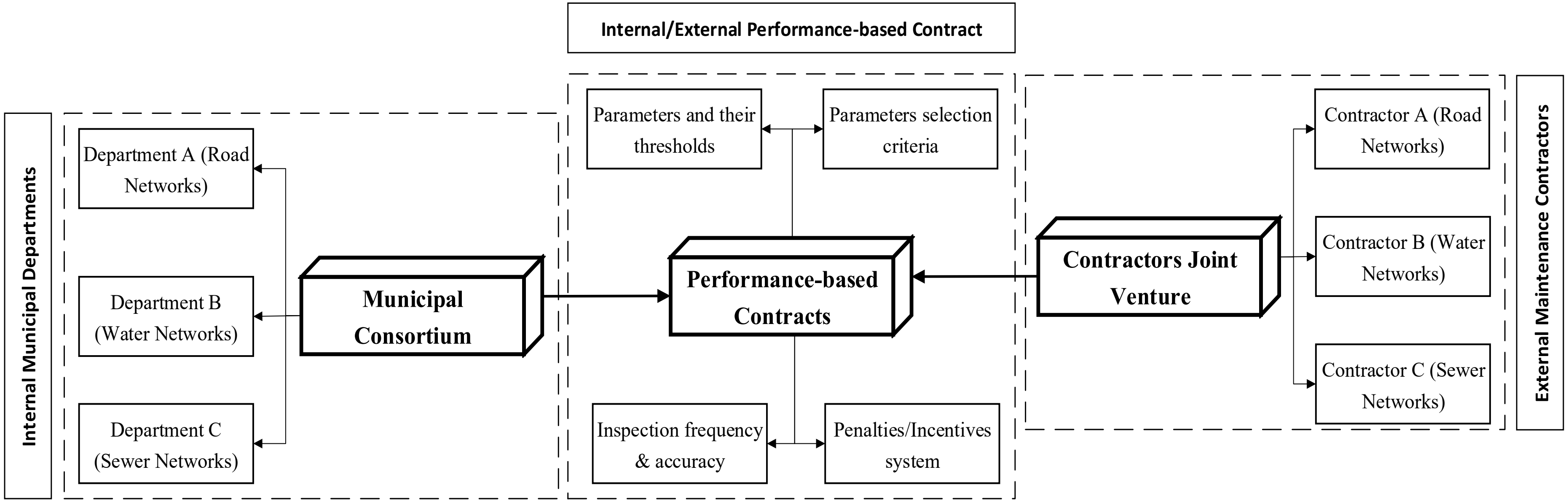


Figure 3.2: *Contractual relationships (Integrated PBC, consortium and joint venture)*

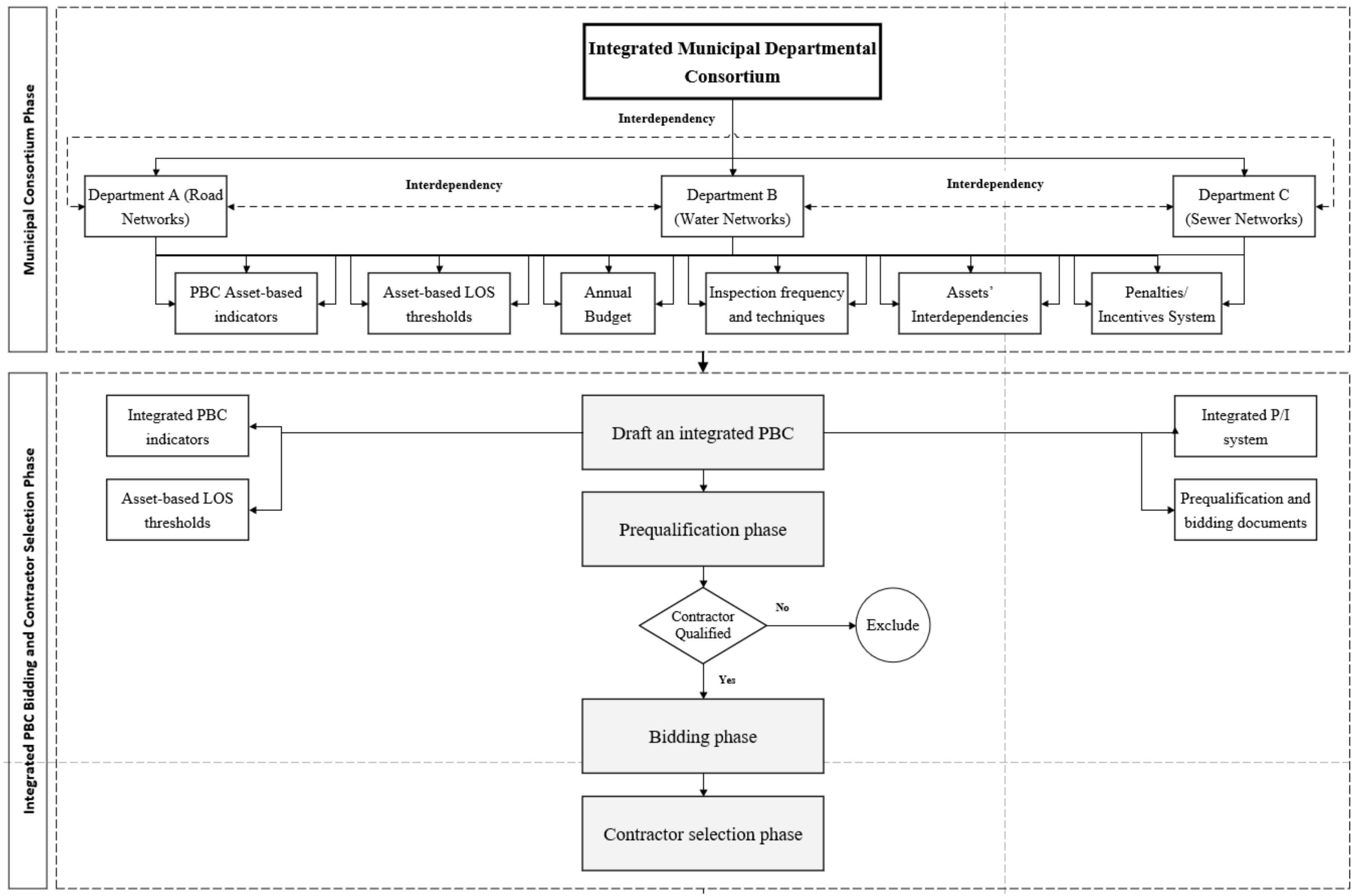


Figure 3.3: *Municipal consortium and prequalification criteria flowchart*

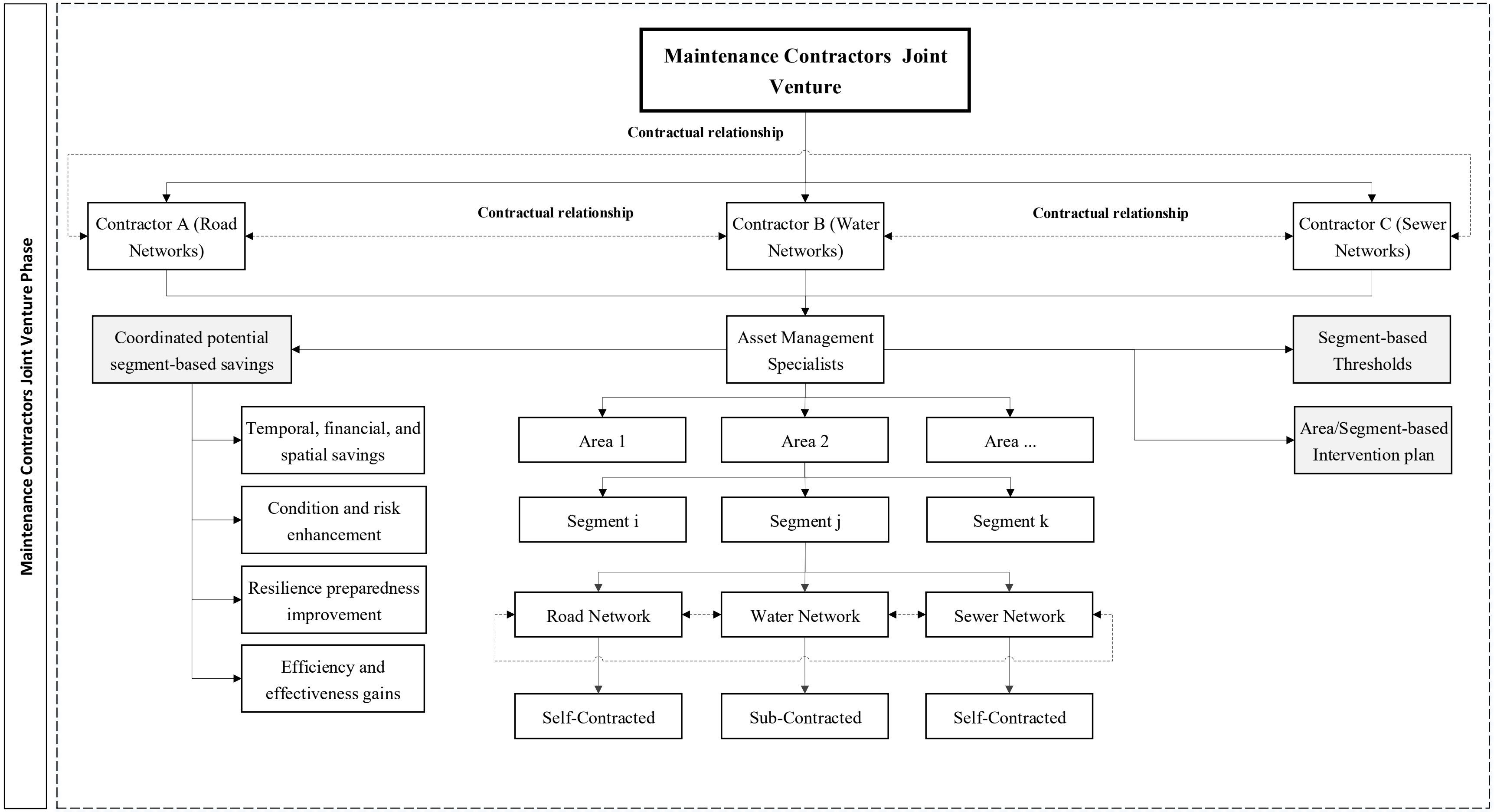


Figure 3.4: *Joint venture flowchart*

3.5 Multi-dimensional Performance Assessment Models

The multi-dimensional performance assessment models are the bridge that links the novel integrated PBC with the asset management system. They quantify the impact of the disruption and consider the advantages of coordinating the interventions. The quantification will result in a better understanding of the spatially co-located activities' coordination benefits. Three coordination scenarios were considered in this research as follows: (1) conventional approach; (2) partially-coordinated; and (3) fully-coordinated. Table **3-3** and Figure 3.5 show the difference between the three coordination scenarios. The conventional approach represents the current municipal practices where the interventions' planning and implementation are undertaken for each asset separately, discarding their interdependencies and potential coordination savings. The partial and full coordination represents the coordination of more than an asset while planning and implementing the interventions. The coordination results in potential savings, represented through KPIs, that are monitored and assessed to compare the coordinated or partially-coordinated intervention scenarios with the conventional scenario in terms of temporal, financial, spatial, efficiency, effectiveness, risk, resilience preparedness, and condition extents. It features through nine integrated models that compute the pre-defined contractual KPIs. The 1st model is the "Duration Savings Model", which basically splits the duration into standalone (asset-based) duration, parallel and joint (shared) duration. After that, it computes the corridor coordination ratio to compare the conventional intervention scenario output, which rests on the basis of asset-based maintenance, with the fully-coordinated and partially-coordinated outputs, which lies on the basis of coordinating the interventions of the right-of-way assets. The 2nd model is the "Spatial Interdependency Savings Model", which computes the spatial and temporal savings of the fully-coordinated, and partially-coordinated coordination scenarios over the conventional scenario. The 3rd model is the "Financial Savings Model", which computes the monetary savings of the fully-coordinated, and partially-coordinated coordination scenarios over the conventional scenario. The financial model incorporates both the direct costs (i.e. manpower, equipment, material) and indirect costs (i.e. disruption – user costs) along with the time value of money while undertaking the trade-off analysis. The 4th and 5th models are the "Intervention Efficiency and Effectiveness Models", which compute the efficiency and effectiveness of coordinating the intervention actions as opposed to undertaking independent intervention actions for each asset. The computations are centered on the core of disruption and operating durations as will be detailed later in this chapter. The 6th model is the "Integrated Deterioration Model", which computes the corridor condition/reliability to reflect the impact of the interventions on the overall corridor condition/reliability. The 7th model is the "Resilience Preparedness Model", which computes the corridor resiliency with respect to climate change and urbanization. The resilience preparedness model focuses only on the water and sewer pipes' replacement given their long service lives and lengthy public disruptions. Furthermore, the resiliency model computes the impact of urbanization, represented through land use change and population increase, and climate change, represented through the rainfall intensity and frequency increase, on the water and combined sewer and stormwater systems. It computes the corridor resilience preparedness of the applied intervention plan on the fully-coordinated, partially-coordinated, and conventional intervention scenarios. The 8th model is the "Risk Model", which computes the corridor's probability and consequences of failure for the fully-coordinated, partially-coordinated, and conventional intervention scenarios and comes up with an improvement factor that reflects the ratio between the coordinated and conventional intervention scenarios. Finally, the 9th model amalgamates the eight above-mentioned indicators into a "Corridor Health Prioritization Model", which calculates a health index for each corridor based on the scores of the indicators to assist asset managers in taking critical intervention decisions and prioritizing the corridors for interventions.

Table 3-3: *Coordination scenarios and the potential combinations*

Coordination Scenarios	Description	Combinations	Coordination Scenario Description
Conventional	The maintenance of each asset is planned and undertaken separately without considering the interdependencies among those systems	Scenario 1: Roads	The roads' interventions are planned separately
		Scenario 2: Water pipes	The water pipes' interventions are planned separately
		Scenario 3: Sewer pipes	The sewer pipes' interventions are planned separately
Partially-coordinated	The maintenance planning and implementation of more than one asset, but not all the potential assets, within the corridor are coordinated	Scenario 4: Roads and water pipes	The roads and water pipes' interventions are coordinated whereas the sewer pipes' interventions are planned separately
		Scenario 5: Roads and sewer pipes	The roads and sewer pipes' interventions are coordinated whereas the water pipes' interventions are planned separately
		Scenario 6: Water and sewer pipes	The water and sewer pipes' interventions are coordinated whereas the roads' interventions are planned separately
Fully-coordinated	The maintenance planning and implementation of all the existing assets within the corridor are coordinated	Scenario 7: Roads, water and sewer pipes	The roads, water, and sewer pipes' interventions are fully coordinated

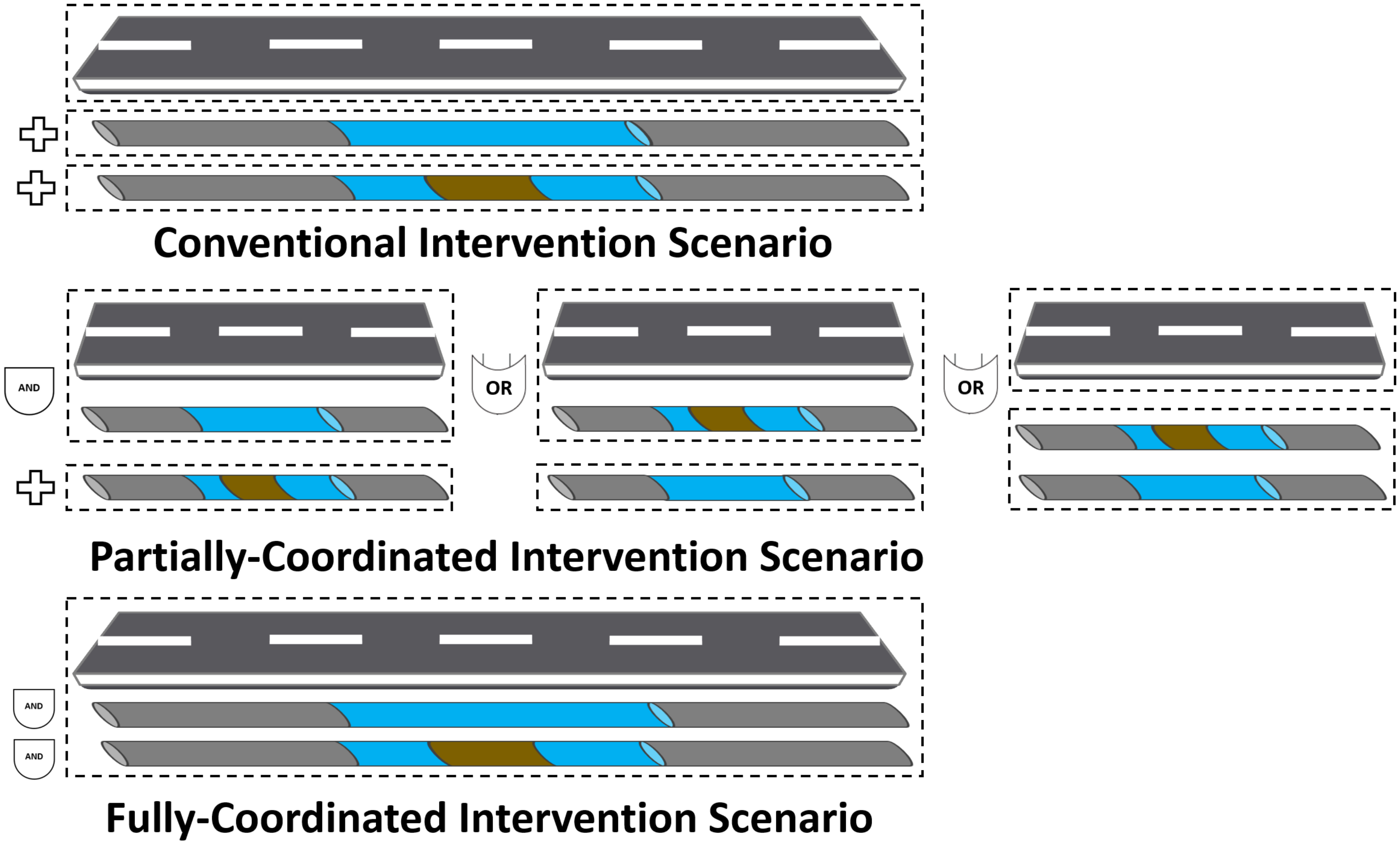


Figure 3.5: *Coordination Scenarios*

3.5.1 *Duration Savings Model*

The duration savings model dynamically computes the duration of the fully-coordinated, partially-coordinated, and conventional interventions, based on the categorized activities and their production rates. The model flowchart is shown in Figure 3.6. The benefit of coordinating the intervention actions is generating time savings in the corridor intervention duration compared to the conventional approach. Those time savings take place because of the existence of joint activities that are shared among the three systems as well as the possibility of undertaking parallel activities rather than series ones in case proper coordination takes place (i.e. road resurfacing can occur concurrently while working on reinstating sewer laterals). As such, these activities can be undertaken only once, in the case of the fully-coordinated approach, rather than n_a or n_s, in the case of the partially-coordinated or the conventional approach, where n is the number of standalone interventions and a and s are the number of systems in cases of partially-coordinated and conventional intervention scenarios respectively. Accordingly, those overlaps can be globalized through the basis of Standalone Duration (SD), Parallel Duration (PD), and Joint Duration (JD), as shown in Figure 3.7. To better understand the theory, let SD_i represent the duration of the intervention activities required only for system *i* and no other work can take place concurrently (i.e. installation of new sewer manholes). Furthermore, let PD_{ijk} represent the duration of the intervention activities that can take place concurrently. Furthermore, let JD_{ijk} represent the duration of the intervention actions required for two or more systems. This duration represents the activities that can take place between two or more systems concurrently (i.e. excavation of entrance and exit pits for water and sewer systems is an example of trenchless rehabilitation for both systems, traffic control devices, excavation and backfilling of common areas, traffic control systems set up, residents' notification, site reinstatement works, etc.). Table 3-4 lists the intervention activities among the three systems along with their duration categories (i.e. SD_i, PD_{ijk}, and JD_{ijk}). Those durations are formulated as the summation of the activities' durations under the same category, as shown through Equations 3.1 to 3.4:

$$SD_{i_{o_t}} = \sum_{m=1}^{M} UR_{m_t} * Q_{m_{o_t}} * IA_{o_{i_{t_r}}} \tag{3.1}$$

$$PD_{ijk_{o_t}} = \sum_{y=1}^{Y} \left(max. \left[UR_{y_t} * Q_{y_{o_t}} * IA_{o_{i_{t_r}}} \right] \right) \tag{3.2}$$

$$JD_{ij_{o_t}} = \sum_{e=1}^{E} UR_{e_t} * Q_{e_{o_t}} * IA_{o_{i_{t_r}}} \tag{3.3}$$

$$JD_{ijk_{o_t}} = \sum_{q=1}^{Q} UR_{q_t} * Q_{q_{o_t}} * IA_{o_{i_{t_r}}} \tag{3.4}$$

where $SD_{i_{o_t}}$ is the standalone duration of system *i* in corridor *o* at point of time *t* (hours); *o* is the corridors' counter (number); t is the point of time in the planning horizon *T* (years); $IA_{o_{i_{t_r}}}$ is a binary intervention applicability index for intervention *r* at time *t* for system *i* within corridor *o* (0 or 1); m, y, e, and q are the counters of the standalone, parallel, and joint activities respectively for system *i, j*, and *k* (number); M, Y, E, and Q are the number of standalone, parallel, and joint activities respectively for systems *i, j*, and *k* (number); UR_{m_t} is the unit rate for activity *m* at point of time *t* (hours/unit); $Q_{m_{o_t}}$ is the quantity of work needed to complete activity m in corridor *o* at point of time *t* (varies according to the units of measurement of the work); $PD_{ijk_{o_t}}$ is the parallel duration for intervention actions of systems *i, j* and *k* in corridor *o* at point of time *t* (hours); $JD_{ij_{o_t}}$ is the joint duration required for intervention actions of systems *i* and *j* of corridor *o* at point of time *t* (hours); and $JD_{ijk_{o_t}}$ is the joint duration required for intervention activities in all the three systems *i, j,* and *k* of corridor *o* at point of time *t* (hours).

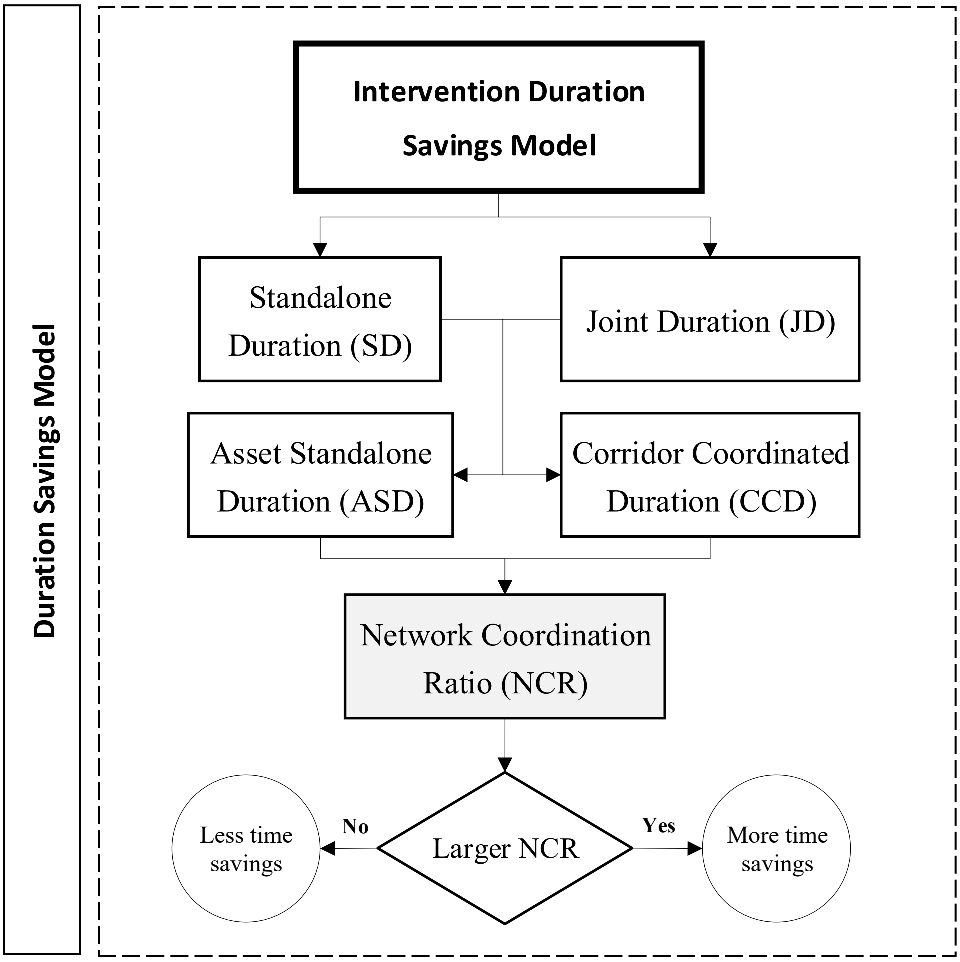


Figure 3.6: *Duration savings model flowchart*

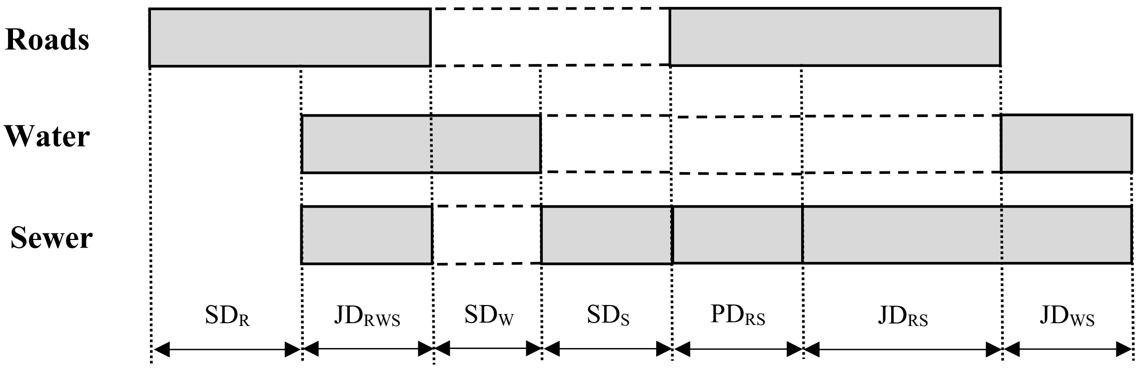


Figure 3.7: *Assets' Durations' categories and relationships*

The model development went through four phases: (1) activities break-down, (2) activities categorization, (3) durations computation, and (4) network coordination ratio computation. The first phase is breaking down the intervention cost centers into tangible activities along with their estimated unit rates, taking into consideration the varying attributes among different corridors (i.e. corridor length, number of residents, soil type, pipe type and diameter, etc.). Then, the second phase is categorizing those activities and identifying the parallel activities for each coordination scenario, as detailed in the corridor intervention activities displayed in Table 3-4. This list represents the main intervention activities that are considered in the system along with their categories, applicability to be undertaken in parallel with other intervention activities, and units of measurements. The list of intervention was identified after conducting an exhaustive literature review on the existing Bill of Quantities (BOQs') and tender documents that include detailed activities list along with their unit rates and costs. However, the system is flexible to add/eliminate any intervention activity, as it is smartly designed to carry out all the financial and temporal computations based on their category and applicability to be undertaken in parallel with other intervention activities. Thus, municipalities and maintenance contractors could input their list of intervention activities and the system will undertake all the necessary computations accordingly.

According to the pre-defined corridor intervention activities list, highlighted in Table 3-4, the unit rates associated with those intervention activities were adopted from several Canadian recent BOQs' and tender documents, taking the time value of money into consideration, as shown in Table 3-5 and Table 3-6. Thenceforth, the unit rates of all n_s systems were validated with the City of Montreal, as detailed in Appendix B. However, given the fact that different municipalities and maintenance contractors have different productivity rates due to several factors such as; maintenance technology, available crew, crew size, number of projects, project scale and extent, availability of experienced crews, etc., the system was designed to flexibly account for different unit rates inputs and the temporal savings will be automatically computed.

Thenceforth, the third phase is computing the durations for three intervention scenarios. Let Asset Standalone Duration (ASD_i) represent the duration of all the intervention activities required for system *i* without interruptions, assuming no coordination takes place; and Corridor Coordinated Duration (CCD) represents the total duration of the entire project, assuming either partial or full coordination scenarios. Finally, the fourth phase is computing the Network Coordination Ratio (NCR), which reflects the potential time savings that could be attained from coordinating the intervention activities, either partially or fully, during the execution phase. The less the NCR is, the less the extent of time savings resulting from the coordination. A ratio of 100% represents no possible time savings due to the absence of either joint activities or activities that can be undertaken in parallel. They could be mathematically formulated as follows:

$$ASD_{i_{o_t}} = SD_{i_{o_t}} + JD_{ijk_{o_t}} + \sum_{i=1}^{n_s} JD_{ij_{o_t}} \; (i \neq j) \tag{3.5}$$

$$CCD_{o_t} = \sum_{i=1}^{n_s} SD_{i_{o_t}} + \sum_{i=1}^{n_s} PD_{ijk_{o_t}} + \left\{JD_{ijk_{o_t}} * n_a\right\} + \sum_{i=1}^{n_s}\sum_{j=1}^{n_s} JD_{ij_{o_t}} \; (i \neq j) \tag{3.6}$$

$$NCR_t = \sum_{o=1}^{O} \left(\frac{\sum_{i=1}^{n_s} ASD_{i_{o_t}}}{CCD_{o_t}}\right) \tag{3.7}$$

$$NCR\,(I_1^{\,-}) = \overline{NCR_t} \tag{3.8}$$

where $ASD_{i_{o_t}}$ is the asset standalone duration for all the systems n_s in corridor *o* at point of time *t* (hours); i is the counter for the systems (number); n_s is the total number of systems (number); CCD_{o_t} is the corridor coordination duration for all the systems n_s in corridor *o* at point of time *t* (hours); n_a is the number of intervention actions that occurred at the same corridor (number); *j* is the counter for the systems (number); NCR_t is the network coordination ratio at point of time *t* (%); O is the total number of corridors (number); and NCR and $\overline{NCR_t}$ are the average network coordination ratio across the planning horizon *T* (%).

Table 3-4: *List of intervention activities along with their categories and units of measurement*

Intervention Activities	Roads (R)	Water (W)	Sewer (S)	Category	Parallel	Unit
Site Reinstatement				JD_{RWS}	Yes	m'
Joint Excavation and Shuttering				JD_{WS}	No	m^3
Sewer Excavation and Shuttering				SD_S	No	m^3
Joint Backfilling and Compaction				SD_{WS}	No	m^3
Sewer Backfilling and Compaction				SD_S	No	m^3
Reinstating Sewer Laterals				SD_S	Yes	No.
Traffic Control Systems				JD_{RWS}	Yes	day
Residents Notification				JD_{RWS}	Yes	No.
Excavation of entrance and exit pits				JD_{WS}	Yes	m^3
Installation of sewer manholes				SD_S	Yes	No.
Water Pipe Repair/Installation				SD_W	Yes	m'
Sewer Pipe Repair/Installation				SD_S	Yes	m'
Surface overlay				SD_R	No	m^2
Road resurfacing				SD_R	No	m^2
Water Pipe Bedding				SD_W	Yes	m'
Sewer Pipe Bedding				SD_S	Yes	m'
Water Main Pipe Leak Repair				SD_W	Yes	leak
Sewer Main Pipe Leak Repair				SD_S	Yes	leak
Water pipe installation (Trenchless)				SD_W	Yes	m'
Sewer pipe installation (Trenchless)				SD_S	Yes	m'

Intervention

No intervention

Table 3-5: *Pipes' intervention repair time per street category per leak (Hachey 2017)*

Road Category	Repair Time (hours)
Local roads	4
Main roads	10
Arterial roads	16

Table 3-6: *Intervention activities unit rates*

Intervention Activities	Unit	Unit Rate (hour/unit)
Site Reinstatement	m'	25
Joint Excavation and Shuttering	m^3	84.82
Sewer Excavation and Shuttering	m^3	84.82
Joint Backfilling and Compaction	m^3	19.22
Sewer Backfilling and Compaction	m^3	19.22
Reinstating Sewer Laterals	No.	6
Traffic Control Systems	day	13.77
Residents Notification	No.	250
Excavation of entrance and exit pits	m^3	60
Installation of sewer manholes	No.	10
Water Pipe Repair/Installation	m'	11
Sewer Pipe Repair/Installation	m'	12
Surface overlay	m^2	1
Road resurfacing	m^2	13
Water Pipe Bedding	m'	15
Sewer Pipe Bedding	m'	16
Water Main Pipe Leak Repair	leak	17
Sewer Main Pipe Leak Repair	leak	18
Water pipe installation (Trenchless)	m'	10
Sewer pipe installation (Trenchless)	m'	8

3.5.2 *Spatial Interdependency Savings Model*

The spatial intervention savings model considers the amount of space needed to be occupied while undertaking any intervention. The spatial interdependency savings model flowchart is shown in Figure 3.8. Based on the lane rental approach (Scott *et al.* 2006), which is applied on the roads for expediting their rehabilitation works, asset managers aim at minimizing the space, time, and disruption caused by maintenance contractors while undertaking the interventions. To better understand the theory, let's assume that A_i is the amount of space needed to be utilized during the rehabilitation for system *i* in the case of no coordination. Therefore, the total area required in case of no coordination will be the sum of the rehabilitation areas of the three right-of-way assets ($A_R+A_W+A_S$), representing the area of roads, water, and sewer respectively, as shown in Equation 3.9. On the other hand, due to the spatial overlap among the systems sharing the same right-of-way, the total area required to undertake the rehabilitation for both the partially-coordinated and fully-coordinated intervention scenarios could be referred to as A_{PC} and A_C and they can be mathematically calculated, as shown in Equations 3.10 and 3.11 respectively. In order to build the model, the extent and required area for each system have been separately identified and spatial interdependencies in partially-coordinated and fully-coordinated intervention scenarios have been identified to compute the above-mentioned areas (A_i, A_j, and A_k). Hence after, the duration model outcomes, $\mathrm{ASD}_{\mathrm{i}_\mathrm{o}}$ and CCD_o, have been used to represent the time a specific area will be occupied for undertaking the rehabilitation. As such, the Spatio-Temporal Disruption Factor (STDF) integrates the spatial and temporal dimensions for conventional, partially-coordinated, and fully-coordinated intervention scenarios, as shown Equations 3.12, 3.13, and 3.14 respectively.

$$A_{CN_{o_t}} = \sum_{i=1}^{n_s} A_{i_t} * IA_{o_{i_{tr}}} \tag{3.9}$$

$$A_{PC_{o_t}} = \left[A_{i_t} + \left(a * A_{j_t}\right) + A_{k_t}\right] * IA_{o_{i_{tr}}} \tag{3.10}$$

$$A_{C_{o_t}} = \left[A_{i_t} + \left(a * A_{j_t}\right) + \left(b * A_{k_t}\right)\right] * IA_{o_{i_{tr}}} \tag{3.11}$$

$$STDF_{CN_t} = \sum_{o=1}^{O} \sum_{i=1}^{n_s} \mathrm{ASD}_{\mathrm{i}_{o_t}} * A_{CN_{o_t}} \tag{3.12}$$

$$STDF_{PC_t} = \sum_{o=1}^{O} CCD_{o_{PC_t}} * A_{PC_{o_t}} \tag{3.13}$$

$$STDF_{C_t} = \sum_{o=1}^{O} CCD_{o_{C_t}} * A_{C_{o_t}} \tag{3.14}$$

where $A_{CN_{o_t}}$ is the maintenance/rehabilitation area of all the systems n_s in corridor o at point of time t for the conventional intervention scenario (m^2); A_{i_t} is the maintenance/rehabilitation area of system i (m^2); $A_{PC_{o_t}}$ is the maintenance/rehabilitation area of all systems n_s in corridor o at point of time t for the partially-coordinated intervention scenario (m^2); a is the percentage of independent area of system j needed to undertake the maintenance/rehabilitation works in the cases of partially-coordinated and fully-coordinated intervention scenarios ($1< a <0$) (%); A_{j_t} is the maintenance/rehabilitation area of system j for both partially-coordinated and fully-coordinated intervention scenarios (m^2); A_{k_t} is the maintenance/rehabilitation area of system k in the case of the fully-coordinated intervention scenario (m^2); $A_{C_{o_t}}$ is the maintenance/rehabilitation area of all systems n_s in corridor *o* at point of time *t* for the fully-coordinated intervention scenario (m^2); b is the percentage of independent area of system *k* needed to undertake the maintenance/rehabilitation works in case of partially-coordinated and fully-coordinated intervention scenario (1< b <0) (%); $STDF_{CN_t}$ is the spatio-temporal disruption factor in the case of conventional network intervention scenario at point of time *t* (%); $STDF_{PC_t}$ is the spatio-temporal disruption factor in the case of partially-coordinated network intervention scenario at point of time *t* (%); and $STDF_{C_t}$ is the spatio-temporal disruption factor in the case of fully-coordinated network intervention scenario at point of time *t* (%).

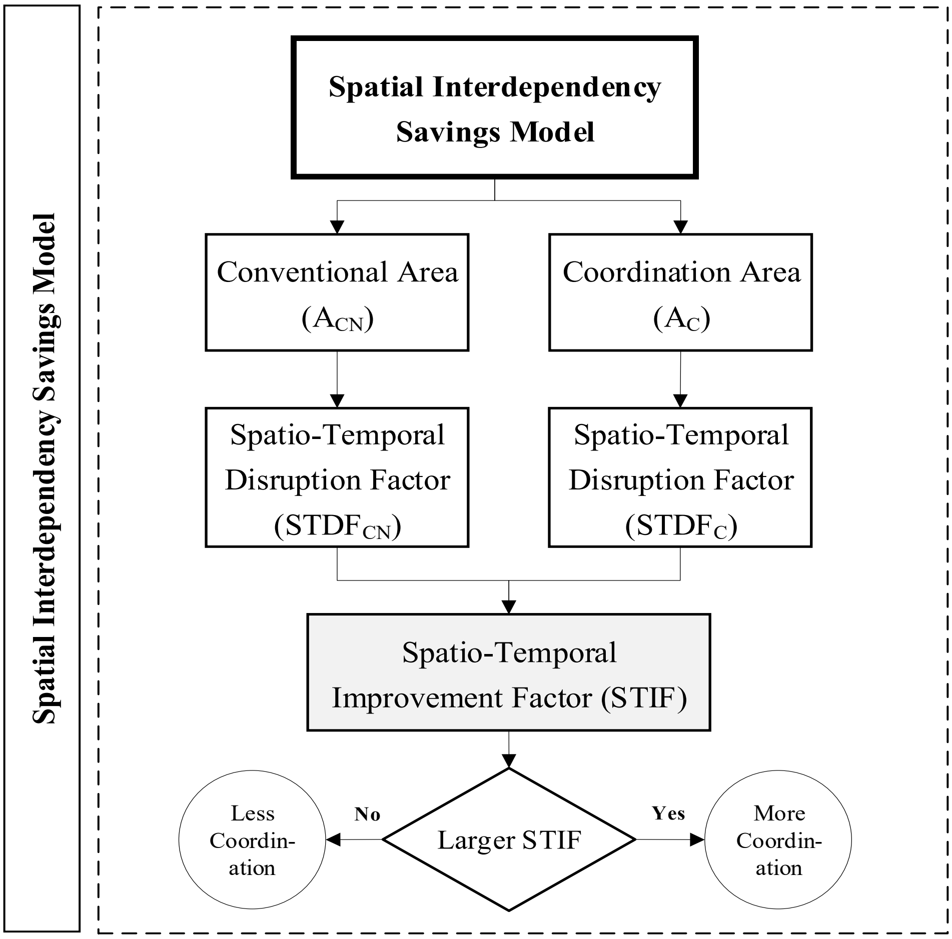


Figure 3.8: *Spatial interdependency savings model flowchart*

The potential spatial savings of the fully-coordinated and partially-coordinated intervention scenarios over the conventional intervention scenario could be visualized in Figure 3.9. It is obvious that the fully-coordinated scenario will consume less area as opposed to the partially-coordinated and conventional scenarios (A_C<A_{PC}<A_{CN}). This is simply because of the spatial interdependency among the co-located assets. For instance, a water or sewer pipe rehabilitation requires demolishing and reconstructing the above road section, causing duplication of work within relatively short time spans and accordingly extra nuisance to the public. Finally, a Spatio-Temporal Improvement Factor (STIF) is computed to compare the fully-coordinated and partially-coordinated intervention scenarios with the conventional one in terms of space and time savings, as shown in Equations 3.15, 3.16, 3.17, and 3.18 respectively. For instance, an STIF of "2" indicates that the considered intervention scenario consumes two times less time and space compared to the conventional intervention scenario.

$$STIF_{PC_t} = \frac{STDF_{CN_t}}{STDF_{PC_t}} \tag{3.15}$$

$$STIF_{C_t} = \frac{STDF_{CN_t}}{STDF_{C_t}} \tag{3.16}$$

$$STIF_{PC}\ (I_2{}^{-}) = \overline{STIF_{PC_t}} \tag{3.17}$$

$$STIF_{C}\ (I_2{}^{-}) = \overline{STIF_{C_t}} \tag{3.18}$$

where $STIF_{PC_t}$ is the spatio-temporal impact factor that compares the partially-coordinated network intervention scenario with the conventional intervention one in terms of space and time at point of time *t* (%); $STIF_{C_t}$ is the spatio-temporal impact factor that compares the fully-coordinated network intervention scenario with the conventional intervention one in terms of space and time at point of time *t* (%); $STIF_{PC}$ and $\overline{STIF_{PC_t}}$ are the average spatio-temporal impact factor that compares the partially-coordinated network intervention scenario with the conventional intervention one in terms of space and time across the planning horizon *T* (%); and $STIF_{C}$ and $\overline{STIF_{C_t}}$ are the average spatio-temporal impact factor that compares the fully-coordinated network intervention scenario with the conventional intervention one in terms of space and time across the planning horizon *T* (%).

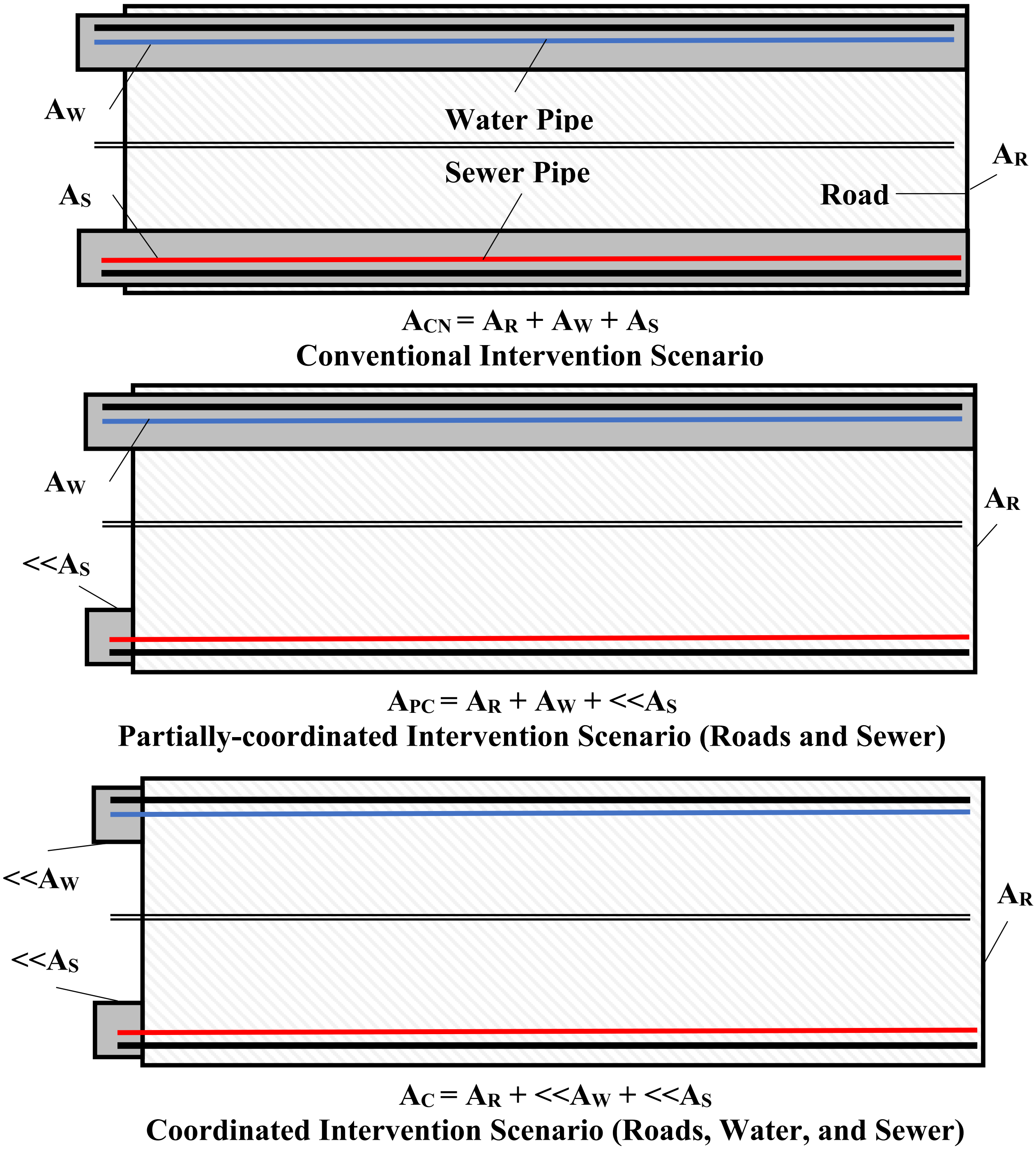


Figure 3.9: *Area savings for different coordination intervention scenarios*

3.5.3 *Financial Savings Model*

The financial savings model calculates the direct and indirect ownership and operational costs of the infrastructure systems, as displayed in Figure 3.10. The direct costs represent the costs of the intervention activities needed to be undertaken throughout the planning horizon to deliver the services in an "acceptable" manner without interruption (i.e. site preparation, residents' notification, installation of traffic control systems, road reconstruction, pipe laying, etc.). On the other hand, the indirect costs, sometimes referred to as "Social" or "User" costs, reflect all the costs that are not directly related to the intervention (i.e. traffic disruption, vehicles or properties repair, business loss, noise disturbance, dirt and dust, environmental or health and safety issues, etc.). Those costs are "*the estimated daily cost to the traveling public resulting from the construction work being performed*" (Daniels *et al.* 1999). They are also "*the consideration of opportunity cost of time for drivers when inconvenienced due to infrastructure overtime*". They refer to the lost time caused by several factors including detours and rerouting that add to travel time; reduced roadway capacity that slows the travel speed and increases the travel time; and delays the opening of a new or improved facility that prevents users from gaining travel time benefits. Accordingly, they were calculated based on the following factors: (1) Average Annual Daily Traffic (AADT) for each corridor; (2) user costs per vehicle per hour; (3) passenger cars vs trucks ratio; (4) corridor speed limit; and (5) intervention time per unit length. Those costs are subjective and rely on probabilistic approaches for predicting their amounts over the systems' service lives (Qin and Cutler 2014; TDOT 2015). The calculations of the indirect costs were based on the output of the duration savings and spatial models to consider the temporal and spatial extent of disruption. In order to compute the LCC for each intervention scenario, the cost centers were divided into three categories: (1) Standalone Direct and Indirect costs for system *i* ($\mathrm{SDC_i}$ and SIC_i), (2) Joint Direct and Indirect cost centers between systems *i* and *j* ($\mathrm{JDC_{ij}}$ and $\mathrm{JIC_{ij}}$), and (3) Joint Direct and Indirect cost centers among systems *i, j*, and *k* ($\mathrm{JDC_{ijk}}$ and $\mathrm{JIC_{ijk}}$). The mathematical computations of the direct and indirect costs for the three categories are shown in the below equations:

$$\mathrm{SDC_i}_{o_t} = \sum_{m=1}^{M} Q_{m_{o_t}} * \mathrm{UC}_{m_t} * IA_{o_{i_{t_r}}} \tag{3.19}$$

$$SIC_{i_{o_t}} = ASD_{i_t} * \frac{A_{i_{o_t}}}{\sum_{i=1}^{ns} A_{i_{o_t}}} * \left[\left((1-\mathrm{T_p}) * \mathrm{AADT} * \mathrm{UUC_T}\right) + \left(\mathrm{T_p} * \mathrm{AADT} * \mathrm{UUC_p}\right)\right] \tag{3.20}$$

$$\mathrm{JDC_{ij}}_{o_t} = \sum_{y=1}^{Y} Q_{y_{o_t}} * \mathrm{UC}_{y_t} * IA_{o_{i_{t_r}}} \tag{3.21}$$

$$\mathrm{JIC_{ij}}_{o_t} = CCD_{o_{PC_t}} * \frac{A_{PC_{o_t}}}{\sum_{i=1}^{ns} A_{i_{o_t}}} * \left[\left((1-\mathrm{T_p}) * \mathrm{AADT} * \mathrm{UUC_T}\right) + \left(\mathrm{T_p} * \mathrm{AADT} * \mathrm{UUC_p}\right)\right] \tag{3.22}$$

$$\mathrm{JDC_{ijk}}_{o_t} = \sum_{e=1}^{E} Q_{e_{o_t}} * \mathrm{UC}_{e_t} * IA_{o_{i_{t_r}}} \tag{3.23}$$

$$\mathrm{JIC_{ijk}}_{o_t} = CCD_{o_{C_t}} * \frac{A_{C_{o_t}}}{\sum_{i=1}^{ns} A_{i_{o_t}}} * \left[\left((1-\mathrm{T_p}) * \mathrm{AADT} * \mathrm{UUC_T}\right) + \left(\mathrm{T_p} * \mathrm{AADT} * \mathrm{UUC_p}\right)\right] \tag{3.24}$$

where $SDC_{i_{o_t}}$ is the total direct costs for the standalone activities of system *i* in corridor *o* at point of time *t* ($); UC_{m_t} is the unit cost for each standalone activity in system *i* at point of time *t* ($); $SIC_{i_{o_t}}$ is the total indirect costs for the standalone activities of system *i* in corridor *o* at point of time *t* ($); $A_{i_{o_t}}$ is the maintenance/rehabilitation area of system *i* at point of time *t* (m^2); T_p is the percentage of trucks (%); AADT is the average annual daily traffic representing the average number of daily vehicles (vehicles); UUC_p is the unit user cost for the passenger cars ($); UUC_T is the unit user cost for the trucks ($); $JDC_{ij_{o_t}}$ is the total direct costs for the joint activities between systems *i* and *j* in corridor *o* at point of time *t* ($); $JIC_{ij_{o_t}}$ is the total indirect costs for the joint activities between systems *i* and *j* in corridor *o* at point of time *t* ($); $CCD_{o_{PC_t}}$ is the corridor coordination duration of corridor *o* for the partially-coordinated intervention scenario at point of time *t* (days); JDC_{ijk_t} is the total direct costs for the joint activities among systems *i, j*, and *k* in corridor *o* at point of time *t* ($); $JIC_{ijk_{o_t}}$ is the total indirect costs for the joint activities among systems *i, j*, and *k* in corridor *o* at point of time *t* ($); and $CCD_{o_{C_t}}$ is the corridor coordinated duration of corridor *o* for the fully-coordinated intervention scenario at point of time *t* (days).

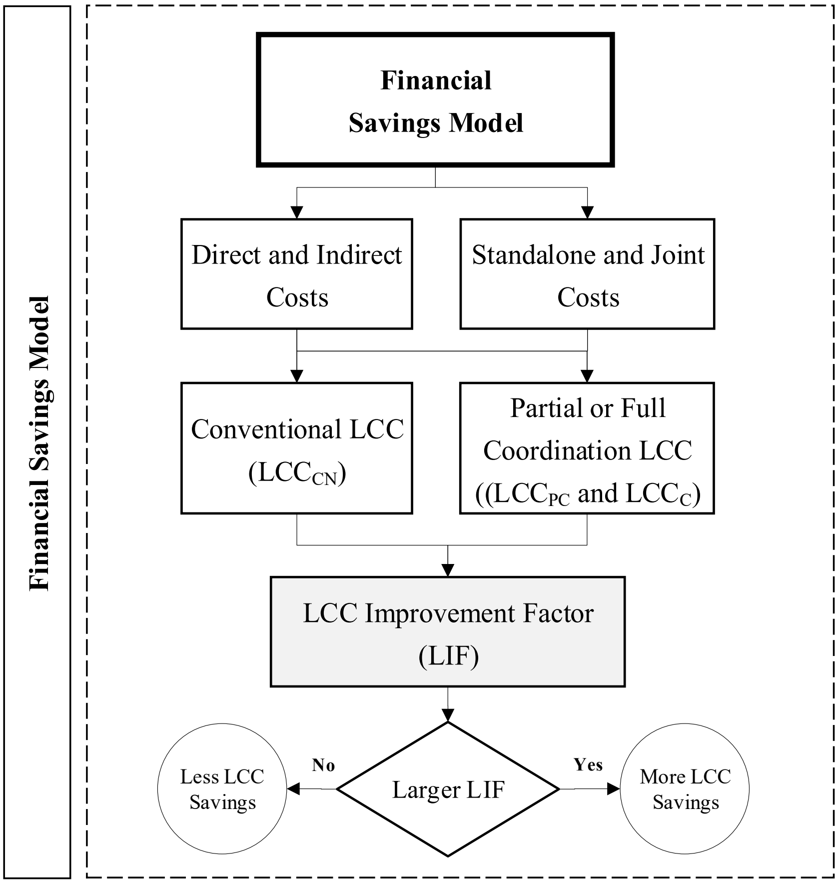


Figure 3.10: *Financial savings model flowchart*

According to the pre-defined corridor intervention activities list, highlighted in Table 3-4, the unit costs associated with those intervention activities were adopted from several Canadian recent BOQs' and tender documents, taking the time value of money into consideration, as shown in Table 3-7 and Table 3-8 (Forterra 2017). Thenceforth, the unit costs of all n_s systems were validated with the City of Montreal, as detailed in Appendix B. However, given the fact that different municipalities and maintenance contractors have different costs due to several factors such as; maintenance technology, available crews, crew size, number of projects, project scale and extent, availability of experienced crews, etc., the system was designed to flexibly account for different unit costs inputs and the financial savings will be computed accordingly.

Table 3-7: *Intervention activities unit costs*

Intervention Activities	Unit	Unit Cost ($/unit)
Site Reinstatement	m'	$660

Intervention Activities	Unit	Unit Cost ($/unit)
Joint Excavation and Shuttering	m^3	$459
Sewer Excavation and Shuttering	m^3	$459
Joint Backfilling and Compaction	m^3	$303
Sewer Backfilling and Compaction	m^3	$303
Reinstating Sewer Laterals	No.	Varies**
Traffic Control Systems	day	$190
Residents Notification	No.	$3
Excavation of entrance and exit pits	m^3	Varies**
Installation of sewer manholes	No.	$950
Water Pipe Repair/Installation	m'	Varies**
Sewer Pipe Repair/Installation	m'	Varies**
Surface overlay	m^2	$25
Road resurfacing	m^2	$65
Water Pipe Bedding	m'	$157
Sewer Pipe Bedding	m'	$157
Water Main Pipe Leak Repair	leak	$825
Sewer Main Pipe Leak Repair	leak	$938
Water pipe installation (Trenchless)	m'	Varies**
Sewer pipe installation (Trenchless)	m'	Varies**

*Varies** represents a varying intervention unit cost depending on the pipe diameter and material*

Table 3-8: *Water intervention repair costs per street category per leak (Hachey 2017)*

Road Category	Repair Costs ($)
Local roads	$ 8,000
Main roads	$ 10,000
Arterial roads	$ 12,000

Thenceforth, the LCC was calculated for the three intervention scenarios. The conventional intervention scenario will result in the highest cost given that all the joint direct and indirect cost centers, either between two systems or among the three systems, will be applied n_s times, drastically increasing the direct and indirect costs. However, the partially-coordinated intervention scenario will experience n_a repetitions for the joint activities as there have been some potential activities that were not coordinated. Thenceforth, the fully-coordinated intervention scenario will not experience any repetitions as the systems were fully-coordinated and all the potentially coordinated activities were applied only once, decreasing the overall costs and the amount/extent of disruption across the planning horizon. Finally, the LCC Improvement Factor (LIF) was calculated to compare the partially-coordinated or fully-coordinated intervention scenarios with the conventional intervention scenario and quantify their potential cost savings. For instance, a LIF of "2" indicates that the fully-coordinated intervention scenario utilizes two times less cost compared to the conventional intervention scenario. The mathematical computations of the LCC and LIF for the three categories are shown in the below equations:

$$C_{CN_{o_t}} = \left[\sum_{i=1}^{n_s}\left(\mathrm{SDC}_{\mathrm{i}_{o_t}} + SIC_{i_{o_t}}\right)\right] + \left[\sum_{i=1}^{n_s}\sum_{j=1}^{n_s}\left(\mathrm{JDC}_{\mathrm{ij}_{o_t}} + \mathrm{JIC}_{\mathrm{ij}_{o_t}}\right) * n_s\right] + \left[\sum_{i=1}^{n_s}\sum_{j=1}^{n_s}\sum_{k=1}^{n_s}\left(\mathrm{JDC}_{\mathrm{ijk}_{o_t}} + \mathrm{JIC}_{\mathrm{ijk}_{o_t}}\right) * n_s\right] + \left[P_{o_t} - I_{o_t}\right] \tag{3.25}$$

$$C_{PC_{o_t}} = \left[\sum_{i=1}^{n_s}\left(\mathrm{SDC}_{\mathrm{i}_{o_t}} + SIC_{i_{o_t}}\right)\right] + \left[\sum_{i=1}^{n_s}\sum_{j=1}^{n_s}\left(\mathrm{JDC}_{\mathrm{ij}_{o_t}} + \mathrm{JIC}_{\mathrm{ij}_{o_t}}\right) * n_a\right] + \left[\sum_{i=1}^{n_s}\sum_{j=1}^{n_s}\sum_{k=1}^{n_s}\left(\mathrm{JDC}_{\mathrm{ijk}_{o_t}} + \mathrm{JIC}_{\mathrm{ijk}_{o_t}}\right) * n_a\right] + \left[P_{o_t} - I_{o_t}\right] \tag{3.26}$$

$$C_{C_{o_t}} = \left[\sum_{i=1}^{n_s}\left(\mathrm{SDC}_{\mathrm{i}_{o_t}} + SIC_{i_{o_t}}\right)\right] + \left[\sum_{i=1}^{n_s}\sum_{j=1}^{n_s}\left(\mathrm{JDC}_{\mathrm{ij}_{o_t}} + \mathrm{JIC}_{\mathrm{ij}_{o_t}}\right)\right] + \left[\sum_{i=1}^{n_s}\sum_{j=1}^{n_s}\sum_{k=1}^{n_s}\left(\mathrm{JDC}_{\mathrm{ijk}_{o_t}} + \mathrm{JIC}_{\mathrm{ijk}_{o_t}}\right)\right] + \left[P_{o_t} - I_{o_t}\right] \tag{3.27}$$

$$LCC_{CN_o} = \sum_{t=1}^{T} C_{CN_{o_t}} \tag{3.28}$$

$$LCC_{PC_o} = \sum_{t=1}^{T} C_{PC_{o_t}} \tag{3.29}$$

$$LCC_{C_o} = \sum_{t=1}^{T} C_{C_{o_t}} \tag{3.30}$$

$$LIF_{PC}\ (I_3^{\,-}) = \sum_{\mathrm{o}=1}^{\mathrm{O}}\left(\frac{LCC_{CN_o}}{LCC_{PC_o}}\right) \tag{3.31}$$

$$LIF_{C}\ (I_3^{\,-}) = \sum_{\mathrm{o}=1}^{\mathrm{O}}\left(\frac{LCC_{CN_o}}{LCC_{C_o}}\right) \tag{3.32}$$

where $C_{CN_{o_t}}$ is the maintenance and rehabilitation costs of corridor *o* for the conventional intervention scenario at point of time *t* (\$); P_{o_t} is the financial penalty applied on corridor *o* for all systems n_s over the planning horizon (\$); I_{o_t} is the financial incentive applied on corridor *o* for all systems n_s over the planning horizon (\$); $C_{PC_{o_t}}$ is the maintenance and rehabilitation of corridor *o* for the partially-coordinated intervention scenario at point of time *t* (\$); $C_{C_{o_t}}$ is the maintenance and rehabilitation of corridor *o* for the fully-coordinated intervention scenario at point of time *t* (\$); LCC_{CN_o} is the life-cycle costs of corridor *o* for the conventional intervention scenario (\$); LCC_{PC_o} is the life-cycle costs of corridor *o* for the partially-coordinated intervention scenario (\$); LCC_{C_o} is the life-cycle costs of corridor *o* for the fully-coordinated intervention scenario (\$); LIF_{PC} is the life-cycle costs impact factor of the partially-coordinated network intervention scenario over the conventional intervention one

(%); and LIF_C is the life-cycle costs impact factor of the fully-coordinated network intervention scenario over the conventional intervention one (%).

3.5.4 *Intervention Efficiency and Effectiveness Models*

The intervention efficiency (utility cut) and effectiveness (free of maintenance) models were developed to support the transition from an "asset stewardship" approach that focuses on cost and condition while undertaking intervention decisions to an "asset serviceability" approach that is centered around the cost, performance, and risk exposure. Moreover, it is well-aligned with the concepts of the PBC such that the assessment is based on the performance and not the level of exerted efforts. In that context, the models introduce efficiency and effectiveness measures to assess the intervention performance over the contractual period, as shown in Figure 3.11. The efficiency represents the percentage of time consumed to undertake all the systems' intervention activities over the total disruption period to restore all the n_s systems. The disruption of the surrounding communities depends on the spacing between the intervention activities. For instance, the disruptive roadway intervention activities that are undertaken immediately after one another will cause more discomfort to the surrounding communities compared to the ones spaced over time. Consequently, many municipalities have taken steps toward implementing measures such as; pavement moratoriums and pavement cutting fees to discourage any excavation within 3-6 years of a road's reconstruction (Wilde *et al.* 2003). In order to better understand the idea, let's assume the time to undertake the intervention as "Disruption Time (DT)", the time between one intervention and another as "Inter-disruption Time (IDT)", and the "Total Disruption Time (TDT)" as the total time to undertake all the interventions for systems n_s, as shown in Figure 3.12. The larger the IDT between the undertaken interventions, the lower the corridor intervention efficiency is, which increases the nuisance to the surrounding environment and the residents will be wondering why those interventions were not coordinated together given the small-time frame they were undertaken at. Accordingly, an Intervention Efficiency Factor (IEF) was computed to assess the overall efficiency of the intervention program for all n_s systems in terms of inter-disruption time extent for the conventional, partially-coordinated, and fully-coordinated intervention scenarios, as shown in Equations 3.33, 3.34, and 3.35 respectively. For instance, an IEF of "1" indicates a superior efficiency of the fully-coordinated intervention scenario in which the IDT is equal to "0" and the TDT is equal to the DT of the fully-coordinated intervention. However, an IEF of “0.5” indicates a 50% DT from the TDT, resulting in discomfort and nuisance to the surrounding environment and residents.

$$\mathrm{I}EF_{\mathrm{CN}}(I_4{}^{-}) = \sum_{o=1}^{0}\left(\frac{\sum_{i=1}^{n_s}\mathrm{DT}_{i_o}}{TDT_o}\right) \tag{3.33}$$

$$\mathrm{I}EF_{\mathrm{PC}}\ (I_4{}^{-}) = \sum_{o=1}^{0}\left(\frac{\sum_{i=1}^{n_s}\sum_{j=1}^{n_s}\mathrm{DT}_{ij_o}+DT_{k_o}}{TDT_o}\right) \tag{3.34}$$

$$\mathrm{I}EF_{\mathrm{C}}\ (I_4{}^{-}) = \sum_{o=1}^{0}\left(\frac{\sum_{i=1}^{n_s}\sum_{j=1}^{n_s}\sum_{k=1}^{n_s}\mathrm{DT}_{ijk_o}}{TDT_o}\right) \tag{3.35}$$

where $\mathrm{I}EF_{\mathrm{CN}}$ is the intervention efficiency factor of the conventional network intervention program for systems n_s in terms of inter-disruption time extent (%); $\mathrm{DT}_{\mathrm{i}_o}$ is the disruption time for system *i* in corridor *o* (days); TDT_o is the total disruption time to undertake all the interventions for systems n_s in corridor *o* (days); $\mathrm{I}EF_{\mathrm{PC}}$ is the intervention efficiency factor of the partially-coordinated network intervention program for systems n_s in terms of inter-disruption time extent (%); $\mathrm{DT}_{\mathrm{ij}_o}$ is the disruption time for systems’ *i* and *j* coordinated intervention in corridor *o* (days); $\mathrm{I}EF_{\mathrm{C}}$ is the intervention efficiency factor of the fully-coordinated network intervention program for systems n_s in terms of inter-disruption time extent (%); k is the counter for the systems (number); and $\mathrm{DT}_{\mathrm{ijk}_o}$ is the disruption time for systems’ *i, j* and *k* coordinated intervention in corridor *o* (days).

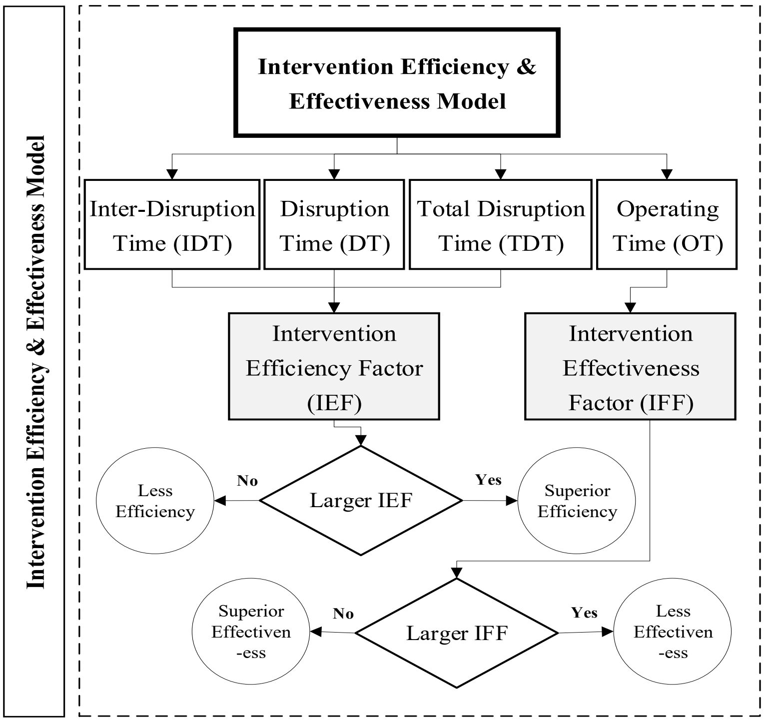


Figure 3.11: *Intervention efficiency and effectiveness model flowchart*

The intervention effectiveness represents the performance/quality of the intervention. In simpler terms, it reflects the amount of operating time expected until the next major intervention, without undertaking any disruptive intervention activities, after the intervention program is accomplished. The time of the next major intervention relies on the following: (1) system's service life and deterioration rate; (2) occurrence of any unforeseeable risk event (i.e. earthquake, severe weather conditions, etc.); (3) compliance with new safety measures (i.e. banned pipe material); (4) system obsolescence; and (5) effectiveness of the undertaken intervention (i.e. condition impact factor, which represents the extent to which the intervention enhances the system's condition state). To better understand the idea, let's assume the time between the corridor's last and next intervention as "Operating Time (OT)". The larger OT reflects higher intervention effectiveness, longer system's service life, and less disruption time. Thus, an Intervention Effectiveness Factor (IFF) was computed to compare the interventions' effectiveness of the partially-coordinated and fully-coordinated intervention scenarios with the conventional one, as shown in Equations 3.36 and 3.37 respectively. If the IFF is less than 1 (IFF<1), the considered coordination scenario reveals improved intervention effectiveness. However, if the IFF is more than 1 (IFF>1), the considered coordination scenario reveals worse intervention effectiveness. For instance, an IFF of "1.2" indicates that the considered coordination scenario has 20% shorter OT compared to the conventional intervention scenario, which implies lower intervention effectiveness. However, an IFF of "0.3" indicates that the considered coordination scenario has 70% longer OT compared to the conventional intervention scenario, which implies superior intervention effectiveness.

$$IFF_{PC}\ ({I_5}^{+}) = \sum_{\text{o}=1}^{\text{O}} \left(\frac{OT_{CN_O}}{OT_{PC_O}}\right) \tag{3.36}$$

$$IFF_{C}\ ({I_5}^{+}) = \sum_{\text{o}=1}^{\text{O}} \left(\frac{OT_{CN_O}}{OT_{C_O}}\right) \tag{3.37}$$

where IFF_{PC} is the intervention effectiveness factor that compares the partially-coordinated network intervention effectiveness with the conventional one in terms of operating time (%); OT_{CN_O} is the operating time of corridor *o* in the case of conventional intervention scenario (days); OT_{PC_O} is the operating time of corridor *o* in the case of partially-coordinated intervention scenario (days); IFF_C is the intervention effectiveness factor that compares the fully-coordinated network intervention effectiveness with the conventional intervention one in terms of OT (%); and OT_{C_O} is the operating time of corridor *o* in the case of the fully-coordinated intervention scenario (days).

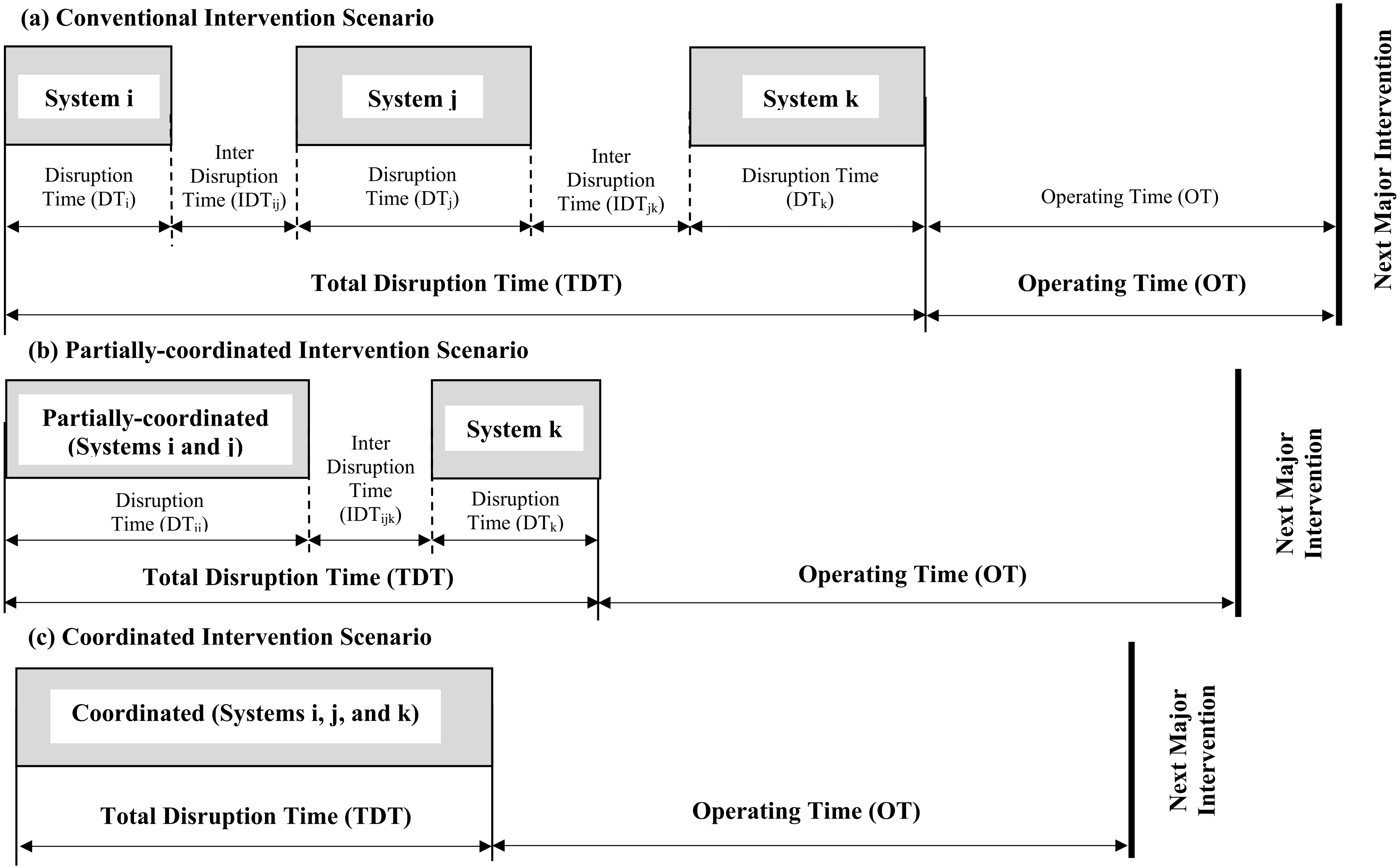


Figure 3.12: *Disruption vs operating time for different intervention scenarios*

3.5.5 *Integrated Deterioration Model*

The integrated corridor-based deterioration model computes the condition/reliability of the corridor, including all the n_s systems, as displayed in Figure 3.13. It features n_s deterioration models for all the n_s systems and compiles their outcomes to a Corridor Condition State (CCS) based on the weights of the importance of each system, as shown in Figure 3.14. Due to their different service lives, deterioration patterns, surrounding conditions, etc., various deterioration models were built for the n_s systems. Based on the outcome of each deterioration model, the Condition/reliability of each system (R_i) at a certain point of time (t) is known for each coordination scenario while considering the intervention actions' effect on the condition/reliability. Accordingly, the systems' condition/reliability are compiled based on the systems' weights of importance and the CCS is computed. The deterioration models were split into two categories: (1) super-corridor; and (2) sub-corridor. The super-corridor represents all the systems that are above the ground level (i.e. roads) whereas the sub-corridor represents all the systems that are below the ground level (i.e. water and sewer networks). Thus, the super-corridor deterioration model was built to represent the roads' condition evolution across the planning horizon while considering the negative impacts (i.e. aging, traffic, freeze and thaw, extreme weather condition, etc.) and positive impacts (i.e. maintenance, rehabilitation, reconstruction). Given the fact that (1) the service lives of the roads are relatively short as opposed to the water and sewer networks; and (2) inspection and condition assessment is easier and less costly, historical condition records of various road types with different traffic levels were available, the super-corridor deterioration pattern was adopted from the town of Kindersley records, as will be detailed later in the Data Collection and Processing chapter (Amador and Magnuson 2011). A sample deterioration equation of the super-corridor is displayed in Equation 3.38. On the other hand, the sub-corridor deterioration model was built to represent the condition evolution of the water and sewer networks across the planning horizon while considering both the negative (i.e. aging, pipe break) and positive impacts (i.e. leak repair, rehabilitation, replacement). Given the fact that (1) the service lives of the water and sewer networks are long (i.e. 60-100 years); and (2) inspection and condition assessment is difficult and costly, Weibull-based deterioration model was used to reflect the deterioration pattern of the pipes across the planning horizon. In order to build a Weibull-based deterioration model, the initial date of installation, estimated service life, alpha, and beta distribution parameters need to be present. Weibull analysis is a widely used technique to analyze and predict failures and malfunctions for different types of assets (Jardine and Tsang 2006). It aims at computing the systems' reliability by calculating the probability density and cumulative distribution functions across the system's service life as displayed in Equations 3.39, and 3.40 respectively. Thenceforth, the system's reliability is computed through Equation 3.41. To account for different pipe materials and diameters, a probability distribution function along with its' distribution function parameters is assigned to each pipe category to account for the different pipe failure curves. The key to plotting the cumulative distribution function as well as the reliability function is properly estimating the shape, scale, and location parameters. The shape parameter, sometimes referred to as Beta (β), is the slope of the cumulative distribution curve and the reliability. It simply reflects the rate of failure for the system such that it designates whether the failure rate is increasing, constant or decreasing. For $\beta<1$, the system has a decreasing failure rate. This scenario is typical of infant mortality and indicates that the system is failing during its initial burn-in period. For $\beta=1$, the system has a constant failure rate. It typically reflects the systems that have survived the initial burn-in period as they will subsequently exhibit a constant failure rate. For $\beta>1$, the system has an increasing failure rate, which represents the systems' in their wearing out period. The scale parameter, sometimes referred to as Alpha (α), is the Weibull attribute life or service life adjustment factor. In other words, it is a measure of the range or spread in the distribution of data. The location parameter, sometimes referred to as Gamma (γ), represents the distribution along the planning horizon (time). For $\gamma=0$, the distribution starts at t=0 (origin). However, the distribution slides to the left or right for $\gamma<0$ or $\gamma>0$ respectively. In this study, the location parameter has been set to zero and the reliability function was computed according to Equation 3.42.

$$R_{i_{o_t}} = \left[0.033 * (t_{i_o})^2\right] - \left[2.688 * t_{i_o}\right] + R_{i_{o_{t_0}}} \tag{3.38}$$

$$d_{i_{o_t}} = \frac{\beta}{\alpha} * \left(\frac{t_{i_o}-\gamma}{\alpha}\right)^{\beta-1} * e^{-\left(\frac{t_{i_o}-\gamma}{\alpha}\right)^{\beta}} \tag{3.39}$$

$$D_{i_{o_t}} = 1 - e^{-\left(\frac{t_{i_o}-\gamma}{\alpha}\right)^{\beta}} \tag{3.40}$$

$$R_{i_{o_t}} = 1 - D_{i_{o_t}} = e^{-\left(\frac{t_{i_o}-\gamma}{\alpha}\right)^{\beta}}\text{; For } \gamma>0 \tag{3.41}$$

$$R_{i_{o_t}} = R_{i_{o_{t_0}}} * e^{-\left(\frac{t_{i_o}}{\alpha}\right)^{\beta}}\text{; For } \gamma=0 \tag{3.42}$$

where t_{i_o} is the age of the system *i* within corridor *o* (years); $R_{i_{o_{t_0}}}$ is the reliability of system *i* within corridor *o* at the initial point of time t_0; $d_{i_{o_t}}$ is the probability density function (deterioration) of system *i* within corridor *o* at point of time *t* (%); β is the shape parameter

(>0); γ is the location parameter (>0); α is the scale parameter (years); $D_{i_{o_t}}$ is the cumulative distribution function (deterioration) of system i within corridor o at point of time t (%); and $R_{i_{o_t}}$ is the reliability of system *i* within corridor *o* at point of time *t* (%).

Random sudden failure may happen to a ratio of systems due to extreme conditions (Mohammed *et al.* 2017). This phenomenon of sudden failure happens randomly to numerous systems at random locations in almost every city where the system experiences a sharp change from a working state to a failing state. However, it is more likely to happen with older systems with lower condition states than others. This type of abrupt service/technical failure may not be adequately represented by the typical deterioration models. Hence, to account for those sudden failures, an extreme event random generator module was developed to enforce sudden failure of 10% of the network under study. This module randomly generates sudden failure to numerous corridors at different points of time. Thenceforth, that information is integrated with the deterioration models of each system and their negative impact is computed through Equation 3.43. This dual deterioration modes' representation would provide decision-makers with more informed decisions that account for real-life cases and enhances the overall network resilience on the long-term accordingly.

$$R_{i_{o_{t_e}}} = \begin{array}{cc} 0\% & Water\ pipe\ break \\ 0\% & Sewer\ pipe\ break \\ R_{i_{o_b}} * 50\% & Road\ extreme\ weather \end{array} \tag{3.43}$$

where $R_{i_{o_{t_e}}}$ is the negative impact of the extreme conditions on the reliability of system *i* within corridor *o* at a point of time *t* (%); and $R_{i_{o_b}}$ is the reliability of system *i* within corridor *o* at a point of time t before the occurrence of an extreme event (%).

Given the spatial interdependency among the systems under study, there are several cases for representing the systems' reliability improvement for each intervention scenario. For instance, a conventional intervention for the roads will only improve the reliability of the roads. However, a conventional intervention for the water or sewer pipe, assuming open-cut replacement, will partially improve the road's reliability, given that the road had to be demolished and reconstructed to access the underneath pipe and replace it with a new one. For the partially-coordinated program, the case when the roads and water or sewer network are integrated will improve the reliability of both systems and will not have any impact on the third system. However, the partially-coordinated water and sewer intervention, assuming open-cut replacement, will improve the reliability of the three systems, given that the road will have to be demolished and reconstructed to access the underneath pipes and replace them with new ones. The fully-coordinated intervention scenario of the roads, water, and sewer network will improve the reliability of the three systems. For simplicity purposes, Table 3-9 summarizes the different coordination scenarios without taking into consideration the different intervention activities (i.e. minor repairs will not return the system to its pristine condition; etc.). Table 3-10 summarizes the impact of the intervention activities on different systems. Furthermore, the impact of the intervention activities on the sub-corridor and super-corridor could be graphically displayed in Figure 3.15 and Figure 3.16. As displayed in those figures, the initial reliability of the system is referred to as R_{INI} and it occurs at the start of the planning horizon T_0. The reliability of the system before and after undertaking the intervention is referred to as R_{BI} and R_{AI} respectively. The impact of the intervention action is referred to as ΔR_I and it takes place on time T_I and the impact takes place at time T_I+1. The reliability threshold is referred to as R_{TH}. In both the sub-corridor and super-corridor cases, the impact of the intervention on the systems' reliability (R_{AI}) is represented through an improvement ($t_{i_{o_{imp}}}$) in their age as displayed in Equation 3.44. However, given the fact that the deterioration pattern and models vary, the mathematical representation of the improvement (ΔR_I) varies. For the sub-corridor case, the mathematical computations of the intervention impact on the Weibull deterioration could be displayed in Equations 3.45 and 3.46. For the super-corridor case, the mathematical computations of the intervention impact on the regression deterioration could be displayed in Equations 3.47 and 3.48.

$$R_{AI_{i_{o_{t+1}}}} = R_{BI_{i_{o_t}}} + \Delta \mathrm{R}_{I_{i_{o_t}}} \tag{3.44}$$

$$R_{AI_{i_{o_{t+1}}}} = R_{i_{o_{t_0}}} * e^{-\left(\frac{t_{i_{o_{imp}}}}{\alpha}\right)^{\beta}} * IA_{o_{i_{tr}}} \tag{3.45}$$

$$\Delta \mathrm{R}_{I_{i_{o_t}}} = \left[R_{i_{o_{t_0}}} * e^{-\left(\frac{t_{i_{o_{imp}}}}{\alpha}\right)^{\beta}} * IA_{o_{i_{tr}}}\right] - \left[R_{i_{o_{t_0}}} * e^{-\left(\frac{t_{i_o}}{\alpha}\right)^{\beta}}\right] \tag{3.46}$$

$$R_{AI_{i_{o_{t+1}}}} = \left[\left[0.033 * (t_{i_{o_{imp}}})^2\right] - \left[2.688 * t_{i_{o_{imp}}}\right] + R_{i_{o_{t_0}}}\right] * IA_{o_{i_{tr}}} \tag{3.47}$$

$$\Delta \mathrm{R}_{I_{i_{o_t}}} = \left[\left[0.033 * (t_{i_{o_{imp}}})^2\right] - \left[2.688 * t_{i_{o_{imp}}}\right] + R_{i_{o_{t_0}}}\right] * IA_{o_{i_{tr}}} - \left[\left[0.033 * (t_{i_o})^2\right] - \left[2.688 * t_{i_o}\right] + R_{i_{o_{t_0}}}\right] \tag{3.48}$$

where $R_{AI_{i_{o_{t+1}}}}$ is the reliability of system *i* within corridor *o* at point of time *t+1* after undertaking intervention *r* (%); $R_{BI_{i_{o_t}}}$ is the reliability of system *i* within corridor *o* at point of time *t* before undertaking intervention *r* (%); $\Delta R_{I_{i_{o_t}}}$ is the reliability improvement of system *i* within corridor *o* at point of time *t* after undertaking intervention *r* (%); and $t_{i_{o_{imp}}}$ is the improved age after undertaking an intervention *r* in system *i* within corridor *o* at point of time *t* (years).

The deterioration models have pre-set condition thresholds that alert the decision-makers in case the condition state of any system reaches a value below the threshold to take rapid intervention decisions and avoid experiencing an increased probability of failure. The corridor condition is computed for the conventional, partially-coordinated, and fully-coordinated intervention scenarios and is represented by CCS_{CN}, CCS_{PC}, and CCS_{C}, as shown in Equations 3.49, 3.50, and 3.51 respectively. Finally, the Condition Improvement Factor (CIF) was computed to compare the partially-coordinated and fully-coordinated intervention scenarios with the conventional one in terms of condition improvement, as shown in Equations 3.52 and 3.53 respectively. If the CIF is less than 1 (CIF<1), the considered intervention scenario displays better condition as opposed to the conventional scenario. However, if the CIF is more than 1 (CIF>1), the considered intervention scenario displays worse condition as opposed to the conventional scenario. For instance, a CIF of "1.2" indicates that the considered intervention scenario displays 20% less condition compared to the conventional one.

$$\mathrm{CCS}_{\mathrm{CN}_o} = \sum_{i=1}^{n_s} \left(W_i * \overline{R_{i_{CN_{o_t}}}} \right) \tag{3.49}$$

$$\mathrm{CCS}_{\mathrm{PC}_o} = \sum_{i=1}^{n_s} \left(W_i * \overline{R_{i_{PC_{o_t}}}} \right) \tag{3.50}$$

$$\mathrm{CCS}_{\mathrm{C}_o} = \sum_{i=1}^{n_s} \left(W_i * \overline{R_{i_{C_{o_t}}}} \right) \tag{3.51}$$

$$CIF_{PC}\ (I_6{}^{+}) = \sum_{o=1}^{O} \left(\frac{L_o}{\sum_{o=1}^{O} L_o} * \frac{CCS_{CN_o}}{CCS_{PC_o}} \right) \tag{3.52}$$

$$CIF_{C}\ (I_6{}^{+}) = \sum_{o=1}^{O} \left(\frac{L_o}{\sum_{o=1}^{O} L_o} * \frac{CCS_{CN_o}}{CCS_{C_o}} \right) \tag{3.53}$$

where CCS_{CN_o} is the corridor condition state of corridor *o* in the conventional intervention scenario (%); W_i is the weight of importance assigned to system *i* (%); L_o represents corridor *o* length (m); $\overline{R_{i_{CN_{o_t}}}}$ is the average reliability of system *i* within corridor *o* across the planning horizon (t) in the conventional intervention scenario (%); CCS_{PC_o} is the corridor condition state of corridor o in the partially-coordinated intervention scenario (%); $\overline{R_{iPC_{o_t}}}$ is the average reliability of system i within corridor o across the planning horizon (t) in the partially-coordinated intervention scenario (%); CCS_{C_o} is the corridor condition state of corridor o in the fully-coordinated intervention scenario (%); $\overline{R_{iC_{o_t}}}$ is the average reliability of system i within corridor o across the planning horizon (t) in the fully-coordinated intervention scenario (%); CIF_{PC} is the condition impact factor that compares the partially-coordinated and conventional network intervention scenarios in terms of condition improvement (%); and CIF_C is the condition impact factor that compares the fully-coordinated and conventional network intervention scenarios in terms of condition improvement (%).

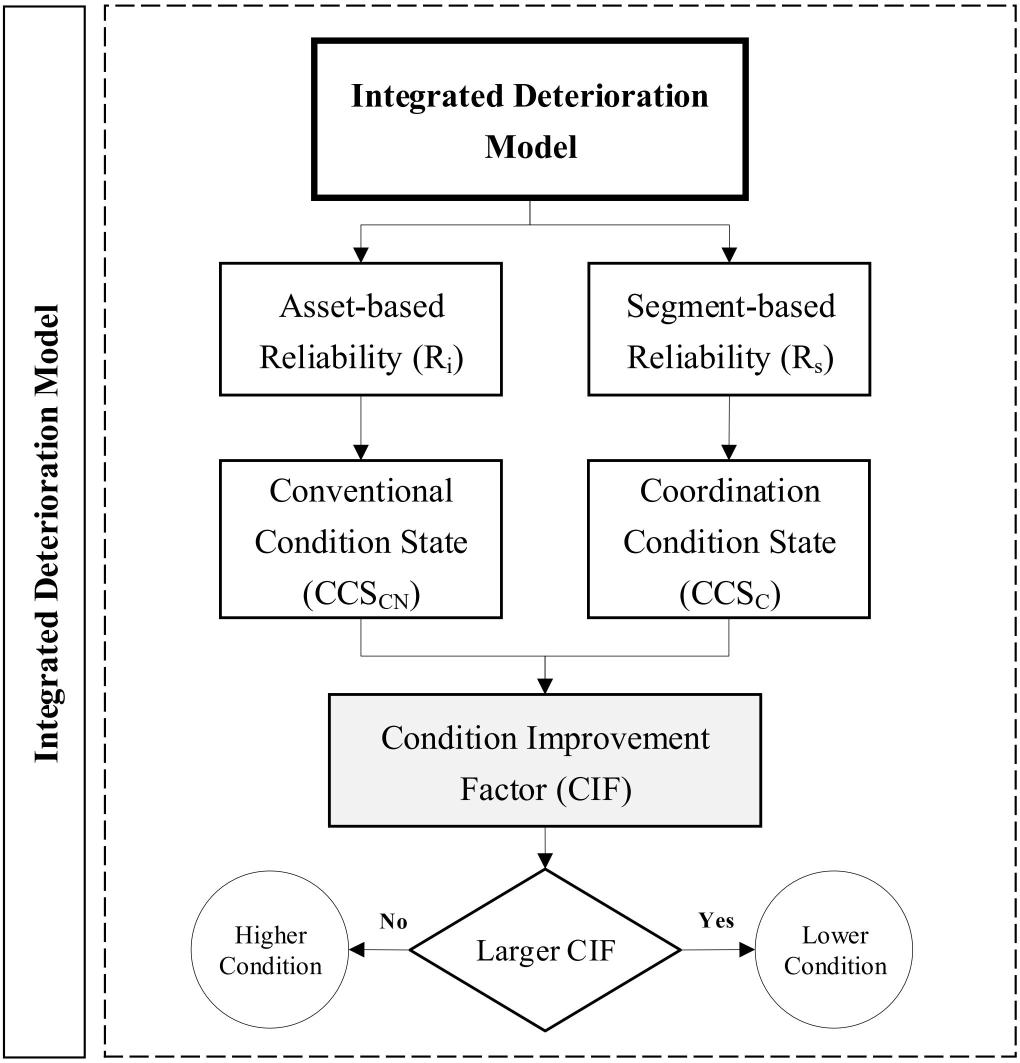


Figure 3.13: *Integrated deterioration model flowchart*

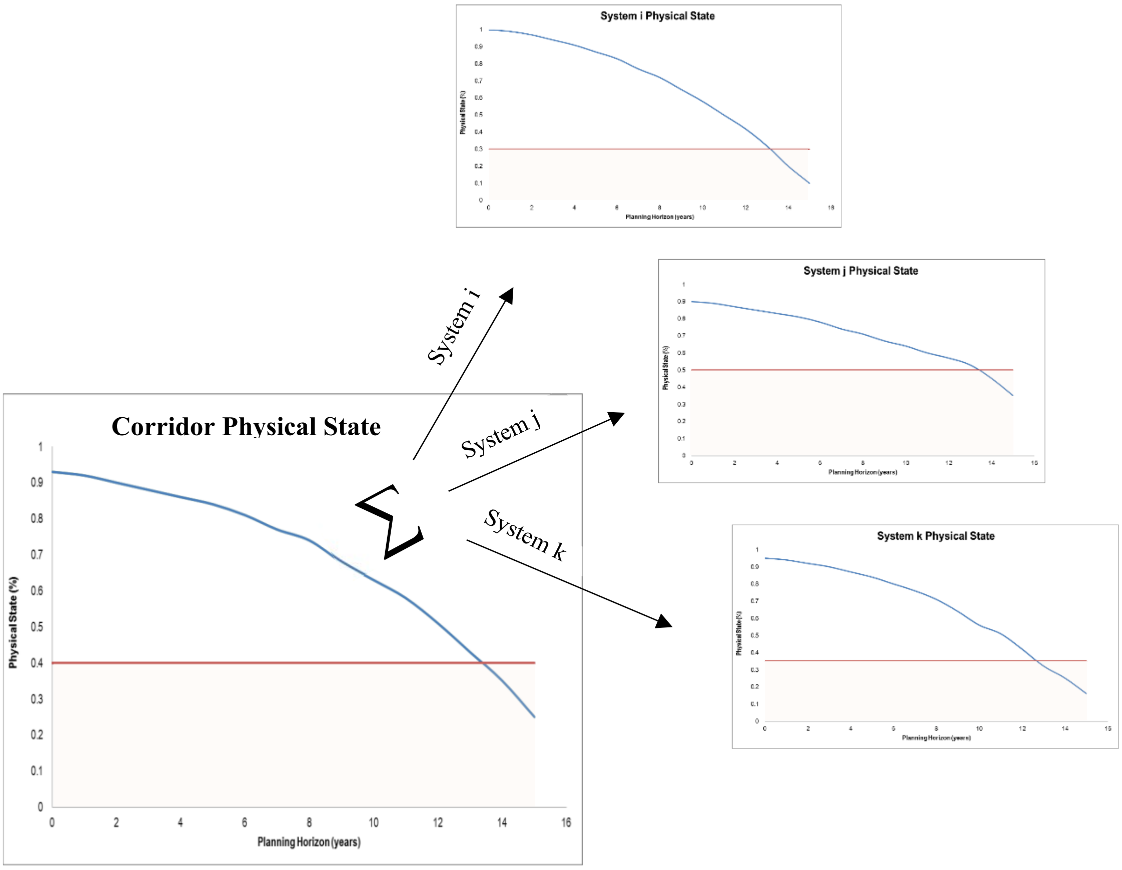


Figure 3.14: *Corridor-based integrated deterioration curves*

Table 3-9: *Intervention-asset impact matrix*

Intervention Scenario	Assets	Road	Water	Sewer
Do Nothing	Do Nothing	×	×	×
Conventional (1 system)	Roads	✓	×	×
	Water	✓	✓	×
	Sewer	✓	×	✓
Partially-coordinated (2 systems)	Roads and Water	✓	✓	×
	Roads and Sewer	✓	×	✓
	Water and Sewer	✓	✓	✓
Fully-coordinated (3 systems)	Full Coordination	✓	✓	✓

Table 3-10: *Intervention reliability impact matrix*

Intervention Description			Intervention Quantitative Effect (ΔR_i)		
Intervention Scenario	Assets	Intervention Action	Roads (Reliability %)	Water (Age - Years)	Sewer (Age - Years)
Do Nothing	Do Nothing	Do Nothing	0%	0	0
	Roads	Surface overlay	Varies*	×	×

Intervention Description			Intervention Quantitative Effect (ΔR_i)		
Intervention Scenario	**Assets**	**Intervention Action**	**Roads (Reliability %)**	**Water (Age - Years)**	**Sewer (Age - Years)**
Conventional (1 system)		Resurfacing	100%	×	×
	Water	Leaks repair	*Varies***	Varies*	×
		Pipe replacement	*Varies***	0	×
	Sewer	Leaks repair	*Varies***	×	Varies*
		Pipe replacement	*Varies***	×	0
Partially-coordinated (2 systems)	Roads and Water	Pipe replacement and road resurfacing	100%	0	×
	Roads and Sewer	Pipe replacement and road resurfacing	100%	×	0
	Water and Sewer	Pipe replacement	*Varies***	0	0
Fully-coordinated (3 systems)	Full Coordination	Pipe replacement and road resurfacing	100%	0	0

0% represents road segments in failing condition states
100% represents road segments in pristine condition state
Varies represents a varying reliability improvement based on the reliability of the system right before undertaking the intervention*
*Varies** represents a varying reliability impact of an intervention depending on the reconstruction area*
0 represents a water or sewer pipe in a pristine condition state
× *represents an asset that has not been affected by the corresponding intervention action*

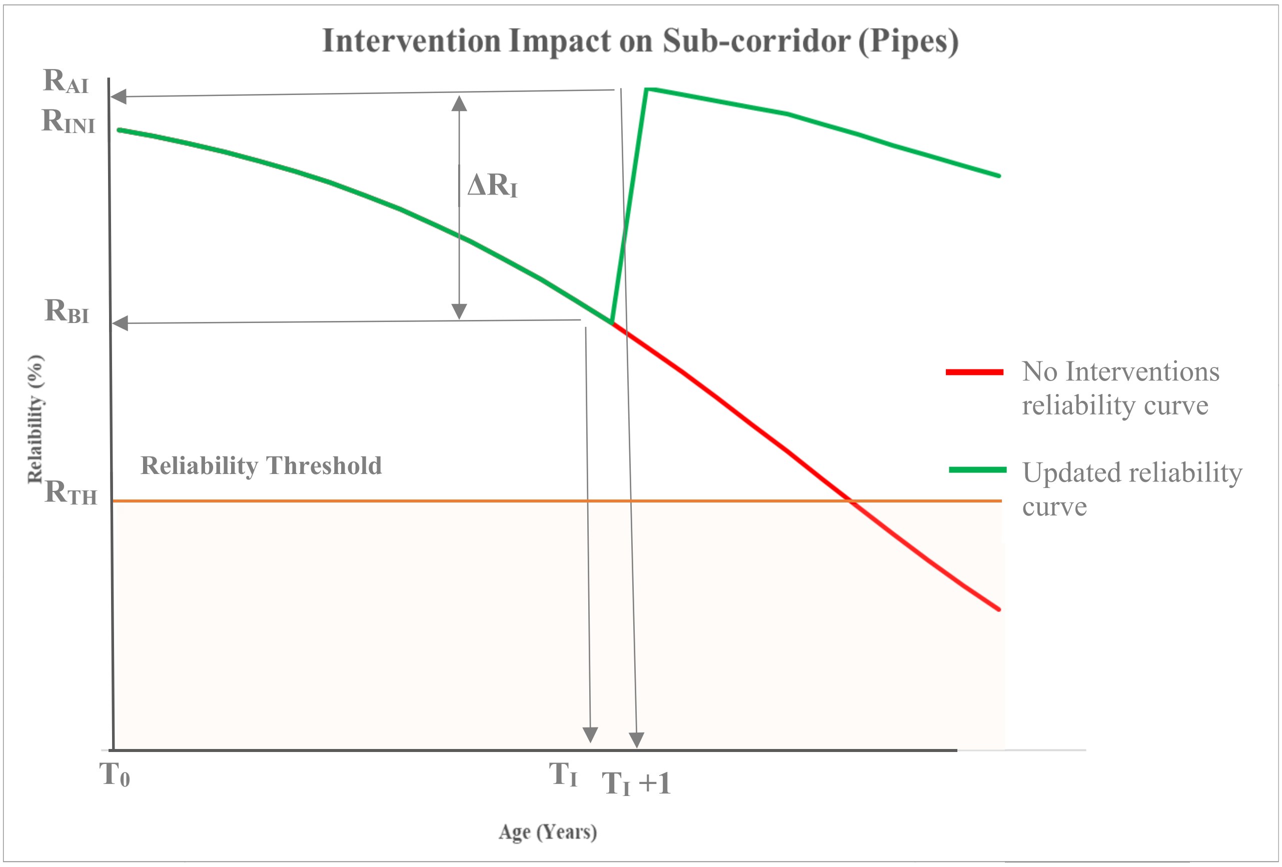


Figure 3.15: *Impact of an intervention on sub-corridor (pipes)*

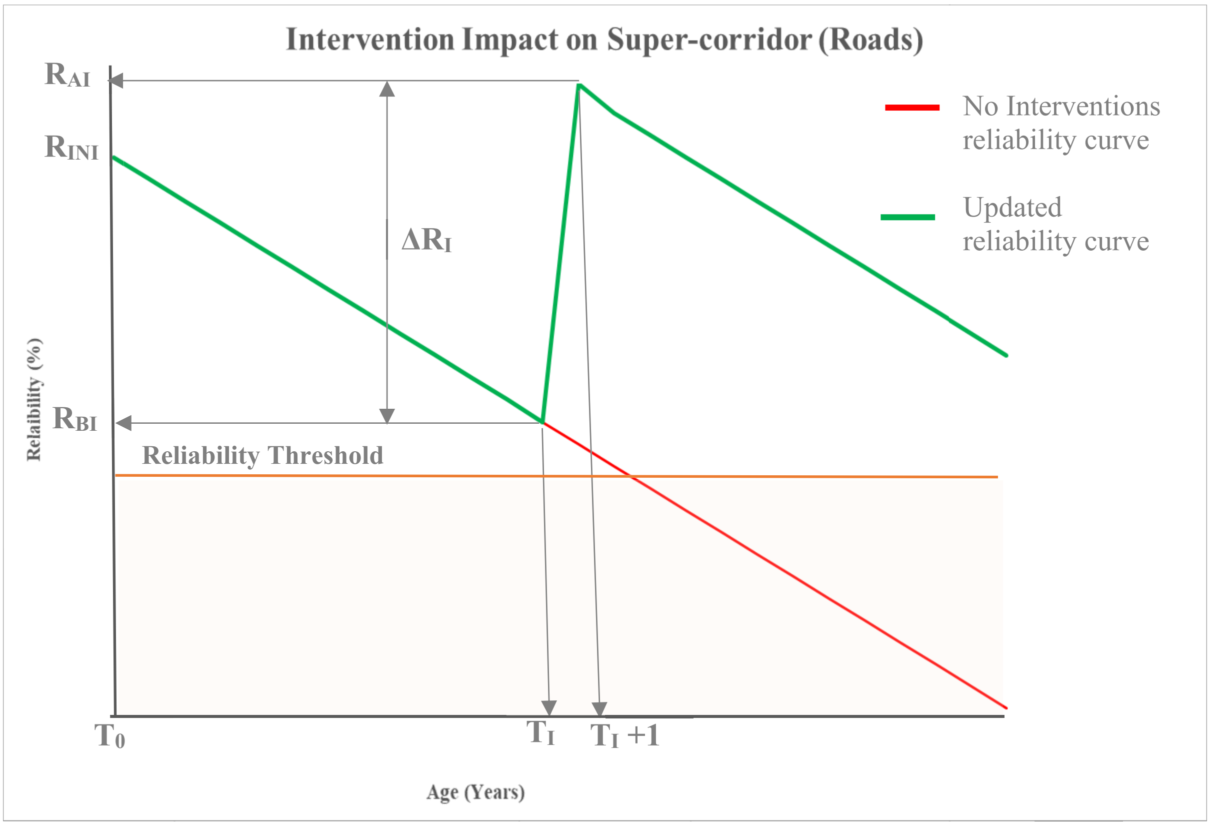


Figure 3.16: *Impact of an intervention on super-corridor (roads)*

3.5.6 *Resilience Preparedness Model*

The resilience preparedness framework supports the transition from a “Reactive” approach, where assets are fixed after failure, to a “Proactive” approach, where asset management plans are developed to prevent assets from failure and prolong the assets’ service lives. It computes the corridors’ resiliency with respect to climate change and urbanization. The resilience preparedness model focuses only on the water and sewer pipes’ replacement given their long service lives and lengthy public disruptions. Furthermore, the resiliency model computes the impact of urbanization, represented through land use change and population growth; and climate change, represented through the rainfall intensity and frequency increase, on the water and combined sewer and stormwater systems. It computes the corridor resilience preparedness of the applied intervention plan on the fully-coordinated, partially-coordinated, and conventional intervention scenarios as shown in Figure 3.17. The model revolves through four integrated models as shown in Figure 3.18: (1) urban and climate change models feed into an urban hydrological model that computes the runoff coefficient and rainfall intensity for each sub-catchment area; (2) capacity performance model that predicts the flow demand-capacity ratios according to the population growth, land use changes for water and combined sewer and stormwater pipes; and climate change, only for combined sewer and stormwater pipes; (3) deterioration model that computes the condition state of the pipes throughout their lifetime, as highlighted in the previous section 3.5.5; and (4) financial model that computes the pipes’ replacement costs, as highlighted in section 3.5.3. The urban hydrological model integrates the outputs of the climate change and urban change models to simulate the impact of rainfall intensity and land use change/population growth on the demand flow of the study areas. For the water pipes, the impact of land use change and population growth are considered to compute the demand flow increase and the increased rainfall intensity will not be considered given that it does not impact the water pipes. However, in the case of combined sewer and stormwater pipes, the impact of climate change, represented through the increased rainfall intensity, are added to the impact of the land use change and population growth. The result of combining those impacts is the increased demand flow. Thenceforth, the capacity performance model computes the current and future flow demand-capacity ratios based on future prediction models’ of the population growth, land use changes, and climate change as will be highlighted later in the upcoming sub-sections. The output of this model is a flow demand-capacity performance curve over the study planning horizon. Accordingly, a demand-capacity ratio greater than 1 (F_{i_t}>1) represents the case when the demand flow exceeds the existing capacity. In that case, the existing pipes need to be replaced with bigger diameter ones to meet the increasing demand flow. Hence after, the deterioration model computes the reliability of the pipes across the planning horizon as highlighted previously in section 3.5.5. Thenceforth, the financial model takes place to compute the pipes' replacement costs over study horizon as highlighted earlier in section 3.5.3. The only difference is that additional alternatives are added to the model to reflect the fact that a pipe could be replaced with a bigger diameter, in case the demand-capacity ratio exceeds 1. In that case, the pipe replacement decisions for both water and sewer networks will be as follows: (1) replacing the pipe with the same diameter/hydraulic capacity in case the current diameter is enough to operate over its' lifetime and the only trigger to replace the pipe was the deteriorating condition state; and (2) increase the hydraulic capacity through installing a larger diameter pipe to account for growing population, increased rainfall intensity, and pipe condition. In the case of larger diameter replacement, the replacement decision trigger will be either (1) operational; where the hydraulic capacity is no longer sufficient to operate; or (2) physical and operational; where both the condition is deteriorating, and the hydraulic capacity is no longer enough for operation. The impact of replacing the pipe with a larger diameter one is considered in the affected models as will be highlighted later.

3.5.6.1 *Computational Models*

A. <u>Urban Hydrological Models</u>

The urban hydrological model aims at computing the rainfall intensity and runoff coefficients of each sub-catchment area to calculate the increase in the demand flow. The runoff coefficient is computed through an urban change model and the rainfall intensity is computed through a climate change model. For the water pipes, the demand flow will be only affected by the runoff coefficient given the fact that they are not affected by the rainfall intensity. However, for the combined sewer and stormwater pipes, both the rainfall intensity and runoff coefficients are considered while computing the demand flow increase. The approach recommended by most drainage manuals is computing the hydrologic response of each sub-catchment to the design storms associated with different return periods. From a drainage perspective, the most dominant characteristic of the urban landscape is the high degree of impervious ground cover. Population growth and changes in urban land-use affect the extent of imperviousness of urban watersheds, leading to a rapid rate of increase on rainfall runoff. These factors result in more significant changes to the hydrologic regime compared with changes due to drainage works in rural and non-developed areas. Furthermore, the volume and rate of stormwater runoff directly rely on the magnitude of precipitation. Statistical frequency analysis of Canadian global climate models' series has shown that rainfall events' frequency and intensity will, most likely, increase over the next years due to the climate change (Environment Canada 2014). Accordingly, statistical downscaling models must be employed to downscale the General Circulation Models (GCMs) based rainfall projections.

The adopted urban change model is centered on the rational method (Dooge 1957). It computes the runoff coefficient and tributary area (*A*) that are affected by current and future land use patterns, which respond to urban growth development strategies. Given the fact that there are various land uses for each sub-catchment area, the runoff coefficient of each pipe *i* is estimated through computing the individual runoff coefficient with respect to each land use type area (A_i). Furthermore, the climate model estimates the changes across time of impervious areas, runoff and flows to the pipe system for an entire catchment based on remotely sensed data and GIS technologies (Thanapura *et al.* 2007; Savary *et al.* 2009; Gupta *et al.* 2012). The output of the climate model is the Rainfall Intensity (*I*), which is estimated from Regional Climate Models (RCMs) and Intensity-Duration-Frequency (IDF). The mathematical formulation of the demand for both runoff coefficient and rainfall intensity could be displayed in Equations 3.54 and 3.55. Thenceforth, the demand of the water and combined sewer and stormwater pipes could be mathematically formulated in Equations 3.56 and 3.57 respectively.

$$RR_{i_{o_t}} = \frac{\sum_{pc=1}^{PC} A_{pc_{i_o}} \times RR_{pc_{i_{o_t}}}}{A_{i_o}} \tag{3.54}$$

$$A_{i_o} = \sum_{pc=1}^{PC} A_{pc_{i_o}} \tag{3.55}$$

$$Q_{i_{o_t}} = RR_{i_{o_t}} * A_{i_o} \tag{3.56}$$

$$Q_{i_{o_t}} = I_t * RR_{i_{o_t}} * \mathrm{A}_{i_o} \tag{3.57}$$

where $Q_{i_{o_t}}$ is the design discharge for the recurrence interval of pipe *i* within corridor *o* at point of time *t* (m^3/day); t is the analysis point of time throughout the planning horizon (years); *i* is the pipes counter; $RR_{i_{o_t}}$ is the rational runoff coefficient of pipe *i* within corridor *o* at point of time *t*; I_t is the rainfall intensity at point of time *t* (mm-h); A_{i_o} is the catchment area of pipe *i* within corridor *o* (m^2); $A_{pc_{i_o}}$ is a fraction of pipe *i* area (A_{i_o}) covered within corridor *o* (m^2); and pc and PC are the counter and total number of components (pc) within pipe *i* area (A_{i_o}) respectively.

After predicting the future impact of the climate change and urbanization, a sub-catchment future prediction model is built to estimate the future discharging of each sub-catchment based on projections of rainfall intensity-duration and land use, only for the combined sewer and stormwater pipes. Similarly, a future demand prediction model is built to estimate the future demand of each water pipe based on land use change as well as population growth. Thenceforth, the flow demand is periodically computed for each pipe over its life-cycle. Different pipes feature different demand curves based on their spatial location. This difference impacts the rainfall intensity, population growth, and land use change. For instance, the population growth in the downtown area is much higher than a residential area. Similarly, the rainfall intensity differs from one area to another.

B. <u>Capacity Performance Model</u>

The capacity performance model aims at computing the flow demand-capacity ratios (*F*). This ratio (*F*) can be used to characterize the system resiliency where it estimates the flow over the capacity ratio of each pipe over its life-cycle to ensure that the flow demand is met by the given pipe diameter. For instance, a ratio above 100% indicates a pipe facing flow demand superior to its capacity. In that case, the model alerts the decision-makers that the current pipe either (1) will experience overflow, in case of combined sewer and stormwater, or (2) will not fit the demand, in case of water. In both cases, it needs to be replaced with a larger diameter pipe to meet the flow demand, as shown in Equation 3.58. As mentioned earlier, different pipes feature different demand-capacity ratios based on their spatial location. Thus, the pipes were categorized into three groups based on their demand (i.e. low, medium, and high). A sample of the combined sewer and stormwater pipes' groups could be displayed in Figure 3.19. Similarly, the demand-flow capacity curves of the water pipes have been constructed as will be detailed later in the next chapter.

$$F_{i_{o_t}} = \begin{bmatrix} Do\ Nothing\ or\ replacement\ with\ same\ diameter & \frac{Q_{i_{o_t}}}{CPi_{o_t}} \\ Replacement\ with\ larger\ diameter & \frac{Q_{i_{o_t}}}{CPi_{new_{o_t}}} \end{bmatrix} \tag{3.58}$$

where $F_{i_{o_t}}$ is the flow demand-capacity ratio of pipe *i* within corridor *o* at point of time *t* (%); CPi_t is the capacity of pipe *i* within corridor *o* at point of time *t* (m^3/day); $CPi_{new_{o_t}}$ is the capacity of new pipe *i* with a larger diameter within corridor *o* at point of time *t* (m^3/day).

C. **Deterioration Model**

The deterioration model aims at predicting the reliability of the pipes across their service lives. A detailed description of the Weibull pipes deterioration was provided in the previous section. However, it is worth noting that the impact of replacing the pipe with a same or larger diameter is the same as both return the system to a pristine condition state as displayed in Equation 3.59.

$$R_{AI{i_o}_{t+1}} = \begin{bmatrix} Do\ Nothing & R_{BI{i_o}_t} - d_{{i_o}_t} \\ Replacement\ with\ same\ or\ larger\ diameter & R_{{i_o}_{t_0}} \end{bmatrix} \tag{3.59}$$

D. **Financial Model**

The financial model opts at calculating the replacement costs of each intervention scenario as highlighted earlier in section 3.5.3. Given the diversity of pipe diameters, depths, and materials, replacement costs are estimated at a pipe level. The replacement costs could even vary within the same pipe at different periods of time given the fact that some pipes might require replacement with larger diameters to account for the increased capacity, resulting from increased rainfall intensity-duration-frequency or land use change or population growth. For instance, a 300 mm diameter pipe could be replaced either by the same diameter pipe or a larger one (i.e. 375mm) depending on future demand. Thus, a flow demand-capacity replacement threshold of 50% has been defined to guarantee a safety margin of 25 years without overflooding or operational-triggered replacement that makes the current pipe diameter no longer sufficient to meet the increasing demand. For instance, a deteriorating pipe with flow demand-capacity less than 50% would be replaced with the same diameter and a deteriorating pipe with flow demand-capacity more than 50% will be replaced with a larger pipe diameter given that their hydraulic capacity will not be enough to meet the increasing future demand (Forterra 2017).

3.5.6.2 *Resilience Preparedness Impact Factor*

The resilience preparedness models have pre-set flow demand-capacity thresholds that alert the decision-makers in case the flow demand-capacity of any system reaches a value above the threshold to take rapid intervention decisions and avoid experiencing either an overflood, in case of combined sewer and stormwater system, or unmet demand, in case of the water system. The Corridor Resiliency Preparedness State (CRPS) is computed for the water and combined sewer and stormwater systems in the conventional, partially-coordinated, and fully-coordinated intervention scenarios and is represented by $CRPS_{CN}$, $CRPS_{PC}$, and $CRPS_{C}$, as shown in Equations 3.60, 3.61, and 3.62 respectively. Finally, the Resilience Preparedness Improvement Factor (RPIF) was computed to compare the partially-coordinated and fully-coordinated intervention scenarios with the conventional one in terms of resilience preparedness improvement, as shown in Equations 3.63 and 3.64 respectively. If the RPIF is less than 1 (RPIF<1), the considered intervention scenario displays better resiliency preparedness as opposed to the conventional scenario. However, if the RPIF is more than 1 (RPIF>1), the considered intervention scenario displays worse resiliency preparedness as opposed to the conventional scenario. For instance, an RPIF of "1.2" indicates that the considered intervention scenario displays 20% better resiliency preparedness compared to the conventional one.

$$\mathrm{CRPS}_{\mathrm{CN}_O} = \sum_{i=1}^{n_s}\left(W_i * \overline{F_{i_{CN_{O_t}}}}\right) \tag{3.60}$$

$$\mathrm{CRPS}_{\mathrm{PC}_O} = \sum_{i=1}^{n_s}\left(W_i * \overline{F_{i_{PC_{O_t}}}}\right) \tag{3.61}$$

$$\mathrm{CRPS}_{\mathrm{C}_O} = \sum_{i=1}^{n_s}\left(W_i * \overline{F_{i_{C_{O_t}}}}\right) \tag{3.62}$$

$$RPIF_{PC}\ ({I_7}^{+}) = \sum_{\mathrm{o}=1}^{\mathrm{O}}\left(\frac{L_O}{\sum_{O=1}^{O} L_O} * \frac{CRPS_{CN_O}}{CRPS_{PC_O}}\right) \tag{3.63}$$

$$RPIF_{C}\ ({I_7}^{+}) = \sum_{\mathrm{o}=1}^{\mathrm{O}}\left(\frac{L_O}{\sum_{O=1}^{O} L_O} * \frac{CRPS_{CN_O}}{CRPS_{C_O}}\right) \tag{3.64}$$

where $CRPS_{CN_O}$ is the corridor resiliency preparedness state of corridor *o* in the conventional intervention scenario (%); W_i is the weight of importance assigned to system *i* (%); L_o represents corridor *o* length (m); $\overline{F_{i_{CN_{O_t}}}}$ is the average flow demand-capacity ratio of system *i* within corridor *o* across the planning horizon (t) in the conventional intervention scenario (%); $CRPS_{PC_O}$ is the corridor resiliency preparedness state of corridor *o* in the partially-coordinated intervention scenario (%); $\overline{F_{i_{PC_{O_t}}}}$ is the average flow demand-capacity ratio of system *i* within corridor *o* across the planning horizon (t) in the partially-coordinated intervention scenario (%); $CRPS_{C_O}$ is the corridor resiliency preparedness state of corridor *o* in the fully-coordinated intervention scenario (%); $\overline{F_{i_{C_{O_t}}}}$ is the average flow demand-capacity ratio of system *i* within corridor *o* across the planning horizon (t) in the fully-coordinated intervention scenario (%); $RPIF_{PC}$ is the resilience preparedness impact factor that compares the partially-coordinated and conventional network intervention scenarios in terms of resiliency preparedness improvement (%); and $RPIF_C$ is the resilience preparedness impact factor that compares the fully-coordinated and conventional network intervention scenarios in terms of resiliency preparedness improvement (%).

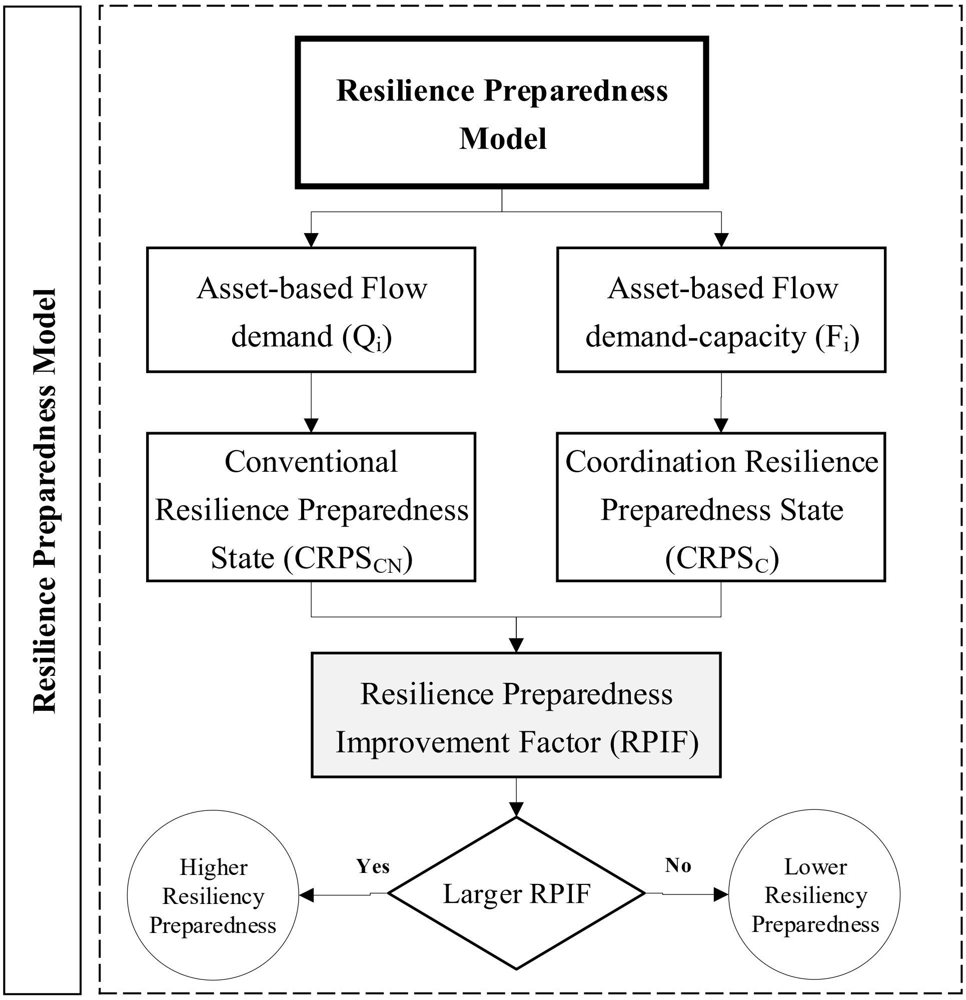


Figure 3.17: *Integrated deterioration model flowchart*

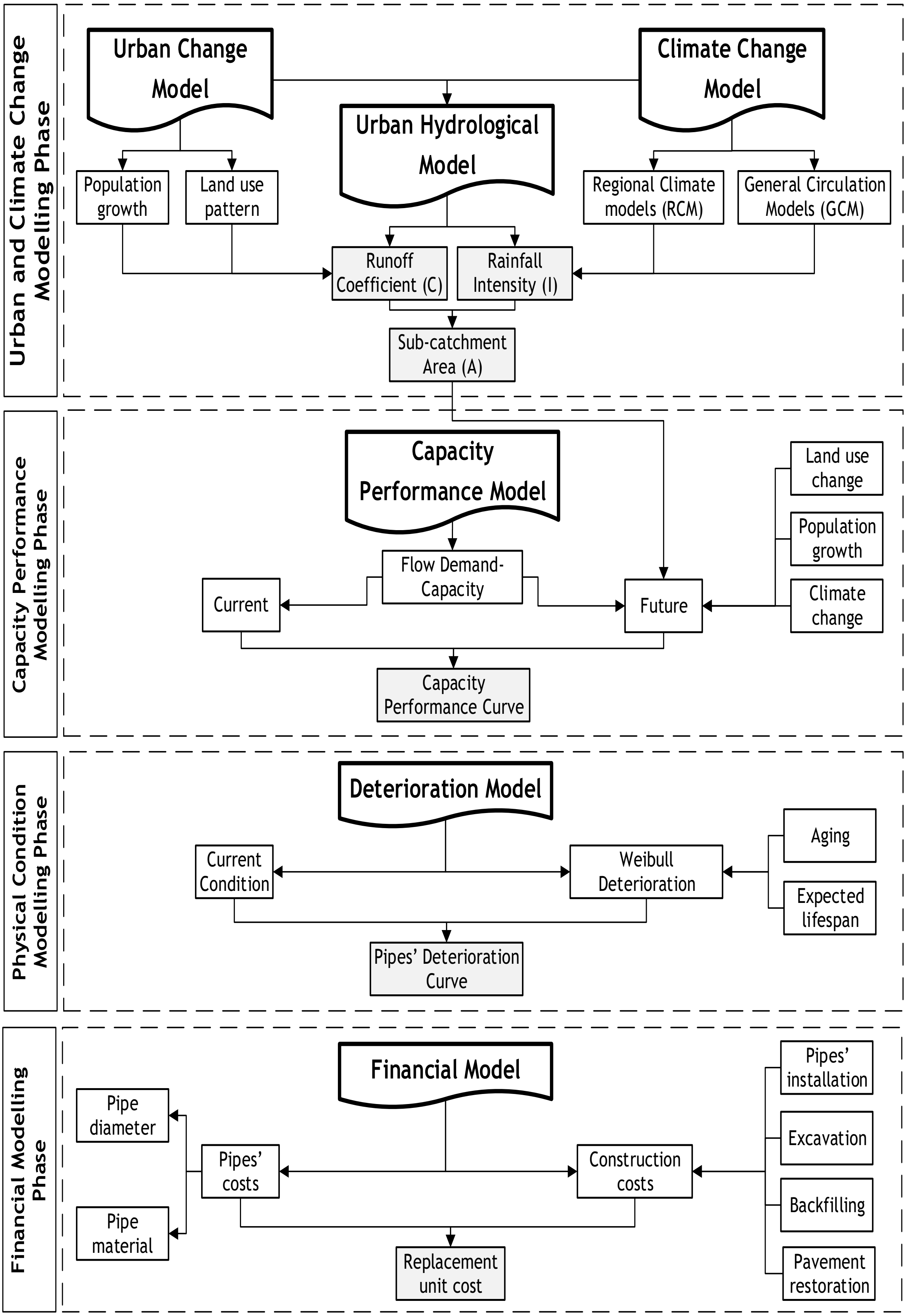


Figure 3.18: *Resilience preparedness methodology*

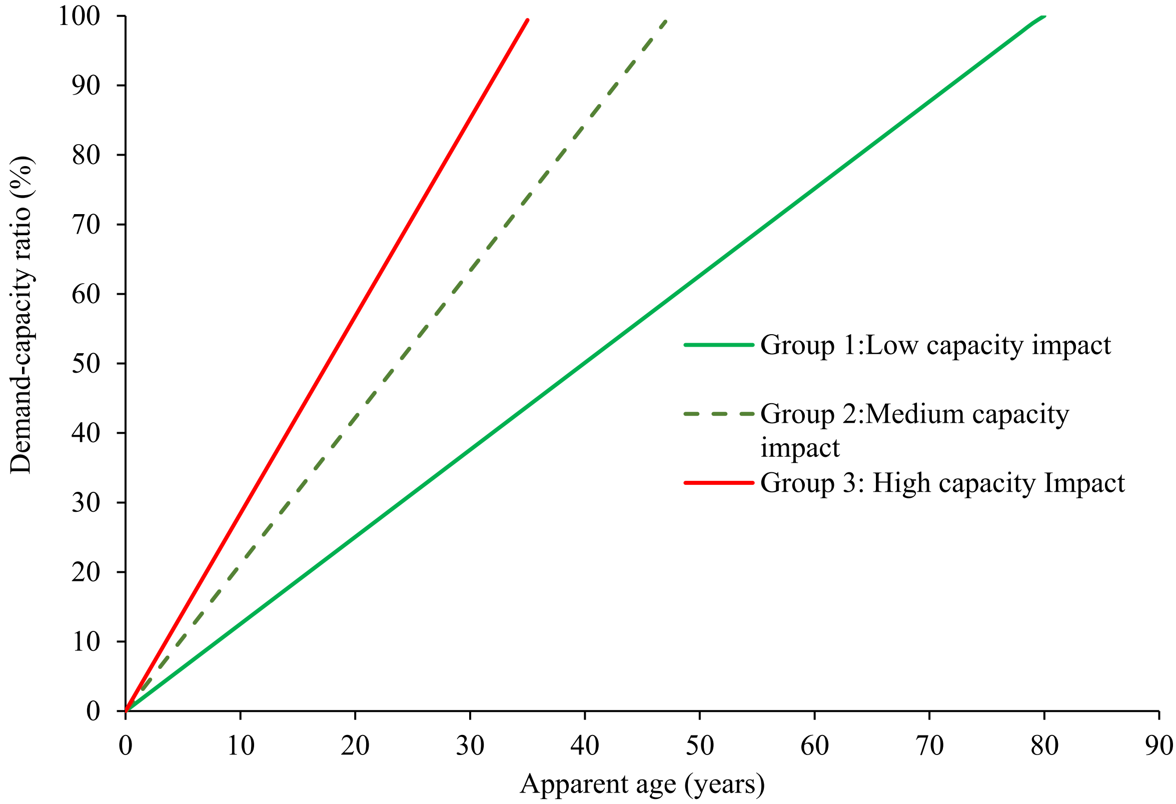


Figure 3.19: *Demand-capacity ratio of different combined sewer and stormwater pipe groups*

3.5.7 *Risk Model*

"*Municipal infrastructure is at risk*", a statement widely spread among decision-makers and stakeholders concerning their municipal infrastructure assets (Shahata and Zayed 2016). Municipalities are faced with challenging decisions to plan the coordinated repair/renewal for the roads, water, and sewer networks, as they are sharing the same right-of-way. It is time for renewal, the cumulative Grade Point Average (GPA) for US corridor infrastructure is "D", water networks are about to end their useful lives, 75% of the wastewater capital needs rehabilitation. In Canada, the corridor infrastructure is in fair condition state, 52% of the roads need further attention, the corridors' replacement cost is estimated at $171.8 billion. In addition, this is reflected by the growing budget deficits among most of the municipalities who suffer lack of collaboration and coordination among various internal and external groups, which results in unnecessary restoration works, duplication of efforts, etc. The risk impact model aims at computing the RI for each corridor through both the POF and COF, as shown in Figure 3.20. Even though different infrastructure systems feature different failure modes and deterioration rates, the POF was independently calculated for each system, based on the current and future condition state, as detailed in the integrated deterioration model section, such that the relation between the POF and reliability is displayed in Equation 3.37. On the other hand, the COF was computed for each system based on the repair costs, loss of revenue, loss of service, loss of life, injury, health and environmental impacts, damage to surrounding infrastructure or property, failure to meet safety regulations, third party losses, loss of image, pollution, contamination, etc. Hence, those parameters were split into four categories, as displayed in Table 3-11. The categories could be best summarized as follows: (1) economic effect of the system's failure on the monetary resources; (2) operational effect of the system's failure on the surrounding society; (3) social effect of the system's failure on the surrounding society; and (4) environmental effect of the system's failure on the surrounding environment.

Table 3-11: *Risk categories along with their parameters*

Effect Category	Parameter
Economic	Repair costs
	Loss of revenue
Operational	Loss of production
	Damage to surrounding infrastructure or property
	Failure to meet safety regulations
Social	Loss of life

Effect Category	Parameter
	Injury
	Loss of service
	Third party losses
	Loss of image
Environmental	Health and environmental impacts
	Pollution
	Contamination

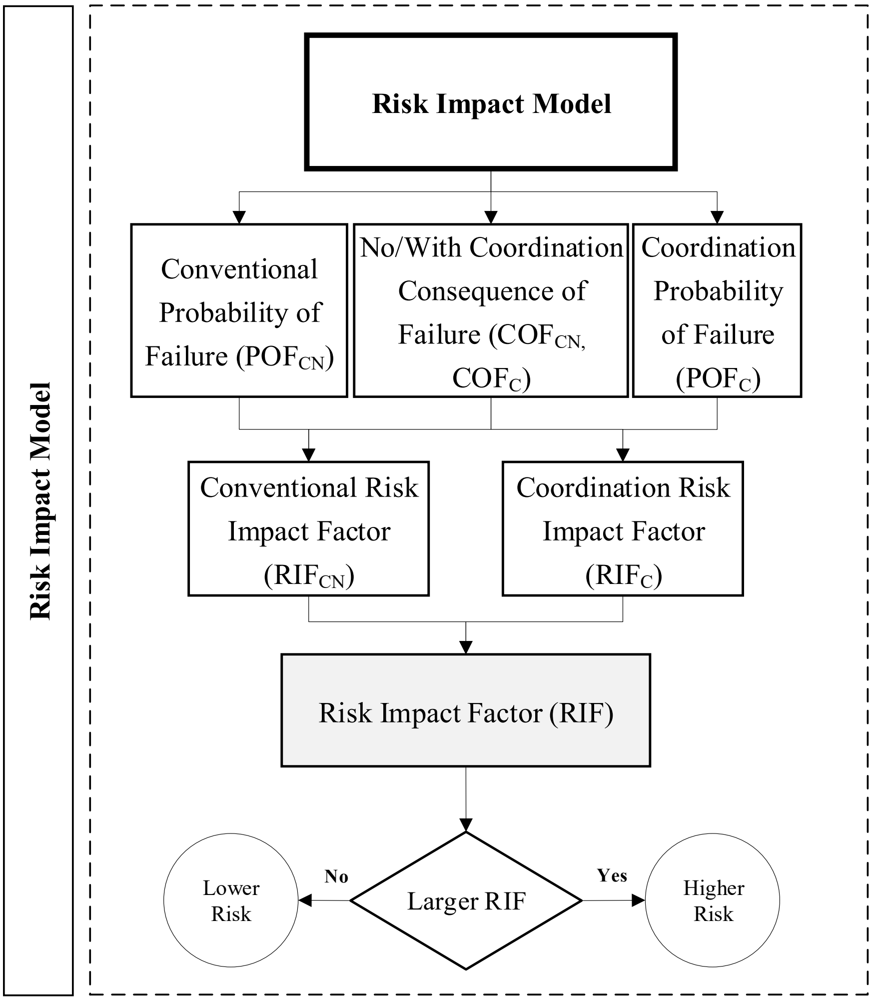


Figure 3.20: *Risk impact model flowchart*

3.5.7.1 *Risk Factors' and Sub-Factors Weights*

Given that the risk factors' assessment is either quantitative or qualitative, a risk scoring system was needed to define and unify the risk assessment criteria among the different factors. The risk factors and sub-factors along with their associated weights were adopted from the literature (Shahata and Zayed 2016). The POF was computed according to the output of the deterioration models for the n_s systems, as highlighted earlier. The COF scoring (SW_{var_r}) ranges between 1 and 5 from insignificant to catastrophic respectively, as shown in Table 3-12. Furthermore, the risk factors and sub-factors along with their weights of importance were defined in Table 3-13. Then, the Decomposed Weight ($\mathrm{DW_{cr}}$) of each sub-factor was calculated by multiplying the main factor (c) weight by its sub-factor weight (W_{var_r}) to represent the overall weight of the sub-factor (r), as displayed in Equation 3.65, and thus, the priority of each sub-factor (r) could be established. Each parameter has several attributes that do not have a similar effect on the COF. For instance, the pipe diameter sub-factor has various values such as; (1) less than or equal 300 mm, (2) 300 – 450 mm, (3) 450 – 750 mm, (4) 750 – 1,200 mm, and (5) greater or equal 1,200 mm. The larger the pipe diameter is, the higher it's COF score (SW_{var_r}) is, representing a higher financial impact in case of failure. The COF is calculated according to Equation 3.66. Similar criteria were established for the other sub-factors to complete the COF calculations, as shown in Table 3-14, Table 3-15, and Table 3-16 for sewer mains, water mains and roads respectively (Shahata 2013). Finally, the consequences of failure costs were estimated for each street category, based on an interview with the city officials, as displayed in Table 3-17 (Hachey 2017).

$$\mathrm{DW_{cr}} = W_{index_c} * W_{var_r} \tag{3.65}$$

$$\mathrm{COF}_o = \sum_i^{n_s} \sum_c^{C} \sum_r^{R} DW_{cr} * SW_{var_{r_{i_o}}} \tag{3.66}$$

where $\mathrm{DW_{cr}}$ is the overall DW for each sub-factor (i.e. sub-factor *r* within factor *c*) (%); W_{index_c} is the weight of each factor (*c*) (i.e. economic, operational, environmental, and social) (%); W_{var_r} is the weight of each sub-factor *r* within the factor *c* (%); COF_o is the COF of corridor *o* including all the n_s systems along with their factors and sub-factors (0-5); *c* and *r* are the counters of the factors and sub-factors respectively (number); C and R are the total number of factors and sub-factors respectively (number); and $SW_{var_{r_{i_o}}}$ is the SW_{var} of sub-factor *r* in system *i* within corridor *o* (1-5).

Table 3-12: *Risk consequences scoring description*

Score	Consequence level	Description
1	Insignificant	No significant impact
		Little or no public exposure
		No impact on health risk
		Can be tolerated indefinitely

Score	Consequence level	Description
2	Minor	Limited public exposure
		Minor health risk
		Can be tolerated for an expected period of time
3	Moderate	Minor public exposure
		Health risk on a small part of the population
		Can be tolerated for a brief period of time (i.e. sufficient to plan and take action)
4	Major	Large part of the population at risk
		Requires expedient and/or emergency measures to address
5	Catastrophic	Major Impact for a large part of the population at risk
		Complete failure of systems
		Requires extreme emergency measures

Table 3-13: *Factors and sub-factors weights and decomposed weights*

Main Factor	Sub-Factor	Sub-factor weight ($\mathbf{W}_{\mathbf{var}_{\mathbf{r}}}$)	Decomposed weight (DW_{cr})
Economic (39%)	Pipe size (Diameter)	19%	7.41%
	Pipe Depth	21%	8.19%
	Material (Type of pipe)	16%	6.24%
	Land use	6%	2.34%
	Accessibility	28%	10.92%
	Road type	10%	3.9%
Operational (27%)	Business disruption – Critical customer	33%	8.91%
	Hydraulic impact	18%	4.86%
	Pipe size (Diameter)	16%	4.32%
	Damage to surrounding assets	33%	8.91%
Environmental (21%)	Water body proximity	18%	3.78%
	Sensitive area	47%	9.87%
	Average daily traffic (road class)	24%	5.04%
	Type of soil	11%	2.31%
Social (13%)	No diversion	40%	5.2%
	Land use	10%	1.3%
	Transit route	20%	2.6%
	Average daily traffic (road class)	30%	3.9%

Table 3-14: *Sewer mains COF variables scoring*

Sewer COF Variables Scores				
	Factors	COF Score	Factors	COF Score
Economic Parameters	***1.1 Pipe Size (Diameter)***		***1.4 Land Use***	
	Less or equal 300 mm	1	Agricultural	1
	300 to 450 mm	2	Park / open space	2
	450 to 750 mm	3	Residential	3
	750 to 1200 mm	4	Commercial	4
	Greater or equal 1200mm	5	Institutional	5
	1.2 Pipe Depth		Industrial	5
	Less or equal 2.0 m	1	***1.5 Accessibility***	

Sewer COF Variables Scores				
	Factors	**COF Score**	**Factors**	**COF Score**
	2.0 to 3.0 m	2	Good	1
	3.0 to 3.5 m	3	Marginal	3
	3.5 to 4.0 m	4	Low	5
	Greater or equal 4.0 m	5	***1.6 Material (Type of Pipe)***	
	1.3 Road type		Poly Vinyl Chloride (PVC)	1
	Local	1	Clay (CT, VC)	2
	Collector	2	Asbestos Cement (AC)	3
	Arterial	3	Corrugated Steel (CS)	3
	Custom (i.e. University)	4	Metallic (STL, DI, CI)	4
	Expressway/highway	5	Concrete (RC)	5
Operational Parameters	***2.1 Business Disruption Critical Customer***		***2.4 Sewer main Blockages***	
	Low	1	Low	1
	High (major users, hospitals, health clinics)	5	Medium	3
	2.2 Damage to surrounding Assets		High	5
	Low	1	***2.5 Pipe Size (Diameter)***	
	Medium	3	Less or equal 300 mm	1
	High	5	300 to 450 mm	2
	2.3 Hydraulic Impact		450 to 750 mm	3
	d/D $\leq$0.5	1	750 to 1200 mm	4
	0.5 – 0.65	2	Greater or equal 1200mm	5
	0.65 – 0.75	3		
	0.75 – 0.85	4		
	d/D $\geq$0.85	5		
Environmental Parameters	***3.1 Water body proximity***		***3.3 Sensitive Area***	
	Greater or equal 200 m away	1	No	1
	101 to 200 m	2	Yes	5
	51 to 100 m	3	***3.4 Type of Soil***	
	5 to 50 m	4	Non-Aggressive	1
	Less or equal 5 m	5	Moderate	2
	3.2 Average Daily Traffic (Road Class)		Aggressive	3
	Low	1	Highly aggressive	5
	Moderate	3		
	Heavy	5		
Environmental Parameters	***4.1 No Diversion***		***4.3 Average Daily Traffic (Road Class)***	
	No	1	Low	1
	Yes	5	Moderate	3
	4.2 Land Use		Heavy	5
	Agricultural	1	***4.4 Transit Route***	
	Park / open space	2	No	1
	Residential	3	Yes	5
	Commercial	4		
	Institutional	5		
	Industrial	5		

Table 3-15: *Water mains COF variables scoring*

Water Mains COF Variables Scores				
	Factors	**COF Score**	**Factors**	**COF Score**
Economic Parameters	***1.1 Pipe Size (Diameter)***		***1.5 Land Use***	
	Less or equal 300 mm	1	Agricultural	1
	300 to 450 mm	2	Park / open space	2
	450 to 750 mm	3	Residential	3
	750 to 1200 mm	4	Commercial	4
	Greater or equal 1200mm	5	Institutional	5
	1.2 Pipe Depth		Industrial	5
	Less or equal 2.0 m	1	***1.6 Material (Type of Pipe)***	
	2.0 to 3.0 m	2	Galvanized Steel (GALV)	5
	3.0 to 3.5 m	3	Steel (ST)	4
	3.5 to 4.0 m	4	Pitted Cast Iron (CIP)	3
	Greater or equal 4.0 m	5	Spun Cast Iron (CIS)	3
	1.3 Road type		Ductile iron (DI)	4
	Local	1	Copper (CU)	5
	Collector	2	Concrete Pressure (CP)	5
	Arterial	3	Asbestos Cement (AC)	3
	Custom (i.e. University)	4	Poly Vinyl Chloride (PVC)	1
	Expressway/highway	5	High-Density Poly Ethylene (HDPE)	2
	1.4 Accessibility		Ductile Iron Hyprotech (DIHY)	2
	Good	1		
	Marginal	3		
	Low	5		
Operational Parameters	***2.1 Business Disruption Critical Customer***		***2.3 Hydraulic Impact***	
	Low	1	Pass	1
	High (major users, hospitals, health clinics)	5	Fail	5
	2.2 Damage to surrounding Assets		***2.4 Pipe Size (Diameter)***	
	Low	1	Less or equal 300 mm	1
	Medium	3	300 to 450 mm	2
	High	5	450 to 750 mm	3
			750 to 1200 mm	4
			Greater or equal 1200mm	5
Environmental Parameters	***3.1 Water body proximity***		***3.3 Sensitive Area***	
	Greater or equal 200 m away	1	No	1
	101 to 200 m	2	Yes	5
	51 to 100 m	3	***3.4 Type of Soil***	
	5 to 50 m	4	Non-Aggressive	1
	Less or equal 5 m	5	Moderate	2
	3.2 Average Daily Traffic (Road Class)		Aggressive	3
	Low	1	Highly aggressive	5

Water Mains COF Variables Scores				
	Factors	**COF Score**	**Factors**	**COF Score**
	Moderate	3		
	Heavy	5		
Environmental Parameters	***4.1 No Diversion***		***4.3 Average Daily Traffic (Road Class)***	
	No	1	Low	1
	Yes	5	Moderate	3
	4.2 Land Use		Heavy	5
	Agricultural	1	***4.4 Transit Route***	
	Park / open space	2	No	1
	Residential	3	Yes	5
	Commercial	4		
	Institutional	5		
	Industrial	5		

Table 3-16: *Roads COF variables scoring*

Roads COF Variables Scores				
	Factors	**COF Score**	**Factors**	**COF Score**
Economic Parameters	***1.1 Road Size (#lanes)***		***1.3 Land Use***	
	Local	1	Agricultural	1
	Collector - 2 lane	1	Park / open space	2
	Collector - 3 lane	2	Residential	3
	Arterial - 2 lane	3	Commercial	4
	Arterial - 3 lane	3	Institutional	5
	Arterial - 4 lane	4	Industrial	5
	Arterial - 5 lane	4	***1.4 Road width***	
	Arterial - 6 lane	5	Less or equal 8.0 m	1
	Expressway - 4 lane	5	8.0 to 12.0 m	2
	1.2 Road type		12.0 to 16.0 m	3
	Local	1	16.0 to 20.0 m	4
	Collector	2	Greater or equal 20.0 m	5
	Arterial	3	***1.5 Road Material GST Granular***	
	Custom (i.e. University)	4	Low-Class Bituminous	2
	Expressway/highway	5	High-Class Bituminous	3
			Asphalt over Concrete	4
			Concrete 1	5
Operational	***2.1 Business Disruption Critical Customer***		***2.3 Road width***	
	Low	1	Less or equal 8.0 m	1
	High (major users, hospitals, health clinics)	5	8.0 to 12.0 m	2
	2.2 Damage to surrounding Assets		12.0 to 16.0 m	3
	Low	1	16.0 to 20.0 m	4
	Medium	3	Greater or equal 20.0 m	5

Roads COF Variables Scores				
Factors		COF Score	Factors	COF Score
	High	5		
Environmental Parameters	***3.1 Water body proximity***		***3.3 Sensitive Area***	
	Greater or equal 200 m away	1	No	1
	101 to 200 m	2	Yes	5
	51 to 100 m	3	***3.4 Type of Soil***	
	5 to 50 m	4	Non-Aggressive	1
	Less or equal 5 m	5	Moderate	2
	3.2 Average Daily Traffic (Road Class)		Aggressive	3
	Low	1	Highly aggressive	5
	Moderate	3		
	Heavy	5		
Environmental Parameters	***4.1 No Diversion***		***4.3 Average Daily Traffic (Road Class)***	
	No	1	Low	1
	Yes	5	Moderate	3
	4.2 Land Use		Heavy	5
	Agricultural	1	***4.4 Transit Route***	
	Park / open space	2	No	1
	Residential	3	Yes	5
	Commercial	4		
	Institutional	5		
	Industrial	5		

Table 3-17: *Consequences of failure per street category for pipes*

Road Category	Length (km)	Percentage from the network (%)	Consequences of failure (per break)
Local roads	1,700	49.18%	$10,400
Main roads	1,254	36.27%	$13,000
Arterial roads	503	14.55%	$15,600

On the other hand, the POF was calculated based on the future deterioration models, highlighted earlier in the integrated deterioration model section. The POF scale ranges between 0 and 1 representing “Rare” and “Almost certain” POF respectively. Furthermore, the ranges of the POF vary according to the systems’ nature of deterioration as well as its’ remaining service life as highlighted in Table 3-18.

Table 3-18: *Probability of failure ranges and reliability relations*

POF score range	POF description	System condition	Reliability values
0.9 - 1	Almost certain	Failing	Roads: $0 < R_r < 30$

POF score range	POF description	System condition	Reliability values
			Water: $1 < R_w < 0.85$
			Sewer: $1 < R_s < 0.9$
0.7 - 0.9	Most Likely	Poor	Roads: $30 < R_r < 45$
			Water: $0.85 < R_w < 0.65$
			Sewer: $0.9 < R_s < 0.7$
0.5 - 0.7	Likely	Fair	Roads: $45 < R_r < 60$
			Water: $0.65 < R_w < 0.35$
			Sewer: $0.7 < R_s < 0.4$
0.25 - 0.5	Unlikely	Good	Roads: $60 < R_r < 80$
			Water: $0.35 < R_w < 0.15$
			Sewer: $0.4 < R_s < 0.2$
0.01 - 0.25	Rare	Excellent	Roads: $80 < R_r < 100$
			Water: $0.15 < R_w < 0.01$
			Sewer: $0.2 < R_s < 0.01$

3.5.7.2 *Risk Index (RI)*

Risk management is an important aspect that affects the decision-making process, given that the infrastructure systems are exposed to some degree of risk during their life-cycle/service life. To calculate the corridor's RI, the corridor was divided into sub-corridor and super-corridor, such that the water and sewer networks represent the sub-corridor and the roads represent the super-corridor. The POF is computed from the previously calculated reliability as displayed in Equation 3.67. Thenceforth, the POF and COF for the sub-corridor were amalgamated using the systems' weights of importance, as shown in Equations 3.68 and 3.69 respectively. However, the POF and COF for the super-corridor are equal to the POF and COF of the roads. Hence after, the RI was calculated for both the sub-corridor and super-corridor as a combination of the POF and COF as shown in Equations 3.70 and 3.71 respectively. Finally, the overall RI at each point of time t across the planning horizon is calculated for the whole corridor based on the weights of the importance of both the sub-corridor and super-corridor, as shown in Equations 3.72 and 3.73.

$$\mathrm{POF}_{\mathrm{i}_{o_t}} = 1 - R_{i_{o_t}} \tag{3.67}$$

$$\mathrm{POF}_{\mathrm{Sub}_{o_t}} = \sum_{i=1}^{n_s} (W_i * POF_{i_{o_t}}) \tag{3.68}$$

$$\mathrm{COF}_{\mathrm{Sub}_{o_t}} = \mathrm{Max}\ (\mathrm{COF}_{i_{o_t}}) \tag{3.69}$$

$$\mathrm{RI}_{\mathrm{Sub}_{o_t}} = \mathrm{POF}_{\mathrm{Sub}_{o_t}} * \mathrm{COF}_{\mathrm{Sub}_{o_t}} \tag{3.70}$$

$$\mathrm{RI}_{\mathrm{Super}_{o_t}} = POF_{Super_{o_t}} * COF_{Super_{o_t}} \tag{3.71}$$

$$\mathrm{RI}_{o_t} = (W_{Sub} * RI_{Sub_{o_t}}) + (W_{Super} * RI_{Super_{o_t}}) \tag{3.72}$$

$$\mathrm{RI}_{o} = \overline{RI_{o_t}} \tag{3.73}$$

where $\mathrm{POF}_{\mathrm{i}_{o_t}}$ is the probability of failure of system *i* in corridor *o* at point of time *t* (%); $R_{i_{o_t}}$ is the condition state/reliability of system *i* in corridor *o* at point of time *t* (%); $\mathrm{POF}_{\mathrm{Sub}_{o_t}}$ is the probability of failure of the sub-corridor of corridor *o* at point of time *t* (%); $\mathrm{COF}_{\mathrm{Sub}_{o_t}}$ is the consequence of failure of the sub-corridor of corridor *o* at point of time *t* (0-5); $\mathrm{COF}_{i_{o_t}}$ is the consequence of failure of system *i* in corridor *o* at point of time *t* (0-5); $\mathrm{RI}_{\mathrm{Sub}_{o_t}}$ is the RI of the sub-corridor in corridor *o* at point of time *t* (0-5); $\mathrm{RI}_{\mathrm{Super}_{o_t}}$ is the risk index of the super-corridor of corridor *o* at point of time *t* (0-5); $POF_{Super_{o_t}}$ is the probability of failure of the super-corridor of corridor *o* at point of time *t* (%); $COF_{Super_{o_t}}$ is the consequence of failure of the super-corridor of corridor *o* at point of time *t* (0-5); RI_{o_t} is the risk index of corridor *o* at point of time *t* (0-5); W_{Sub} is the weight of importance assigned to the sub-corridor (%); W_{Super} is the weight of importance assigned to the super-corridor (%); and RI_o and $\overline{RI_{o_t}}$ are the average risk index for corridor *o* across the planning horizon (%).

Finally, the Risk Improvement Factor (RIF) is calculated for the partially-coordinated and fully-coordinated intervention scenarios as the POF changes according to the intervention actions. For instance, at the first intervention of the conventional intervention scenario, the POF of the two non-rehabilitated assets will be high as their reliability/condition states are low. However, at the time of the first intervention in the full coordination scenario, the POF of the three assets will be low as their reliability/condition states are high. Accordingly, the RIF computes the risk improvements of the partially-coordinated and fully-coordinated intervention scenarios compared to the conventional intervention scenario, as shown in Equations 3.74 and 3.75 respectively. The RI of each coordination scenario is computed based on Equation 3.72. If the RIF is more than 1 (RIF>1), the considered coordination scenario reveals less risk exposure compared to the conventional scenario. However, if the RIF is less than 1 (RIF<1), the considered coordination scenario reveals higher risk exposure compared to the conventional scenario. For instance, a RIF of "1.6" indicates that the considered intervention scenario has 60% less risk exposure compared to the conventional intervention scenario.

$$RIF_{PC}\ (I_8{}^{-}) = \sum_{o=1}^{O}(\frac{RI_{CN_O}}{RI_{PC_O}}) \tag{3.74}$$

$$RIF_{C}\ (I_8{}^{-}) = \sum_{o=1}^{O}(\frac{RI_{CN_O}}{RI_{C_O}}) \tag{3.75}$$

where RIF_{PC} is the RIF of the partially-coordinated network intervention scenario as opposed to the conventional intervention one (%); RI_{CN_O} is the RI of corridor *o* in the conventional intervention scenario (0-5); RI_{PC_O} is the RI of corridor *o* in the partially-coordinated intervention scenario (0-5); RIF_C is the RIF of the fully-coordinated network intervention scenario as opposed to the conventional intervention one (%); and RI_{C_O} is the RI of corridor *o* in the fully-coordinated intervention scenario (0-5).

3.5.8 *Corridor Health Prioritization Model*

The corridor health prioritization model was developed to integrate the previously-developed models together and assist decision-makers in prioritizing the corridors for interventions as shown in Figure 3.21. The idea was inspired by the structural health monitoring system, which monitors the health of the structure throughout its' life-cycle time. However, in an infrastructure context, the corridor health will monitor the overall health of the corridor in terms of: (1) time, (2) space, (3) cost, (4) efficiency, (5) effectiveness, (6) condition, (7) resilience preparedness, and (8) risk. To develop the model, each factor was assigned a weight of importance that represents its contribution to the overall corridor health. The weight of the importance of each factor varies from one municipality to another, and even from one area/corridor to another, according to their needs. For instance, a municipality that is facing tough budgetary constraint will give higher weight to the cost. Another case could be a critical area with mixed residential and commercial facilities, such that higher weights will be assigned to the time and space factors to minimize the disruption impacts on the surrounding communities. A corridor in an area that features numerous events will receive higher weights of importance on the time and space factors as longer disruption times will result in extremely high financial consequences of failure. Table 3-19 summarizes the different cases along with their basis, assigned weights, and an illustrative example. In this study, the cost, condition, and risk were assigned the highest weights due to the tough budgetary constraints, arising from the increasing budget deficits, low assets' condition, which reflects the reactive intervention planning approach followed by the municipalities, and the low assets' reliability, which has already resulted in numerous failures.

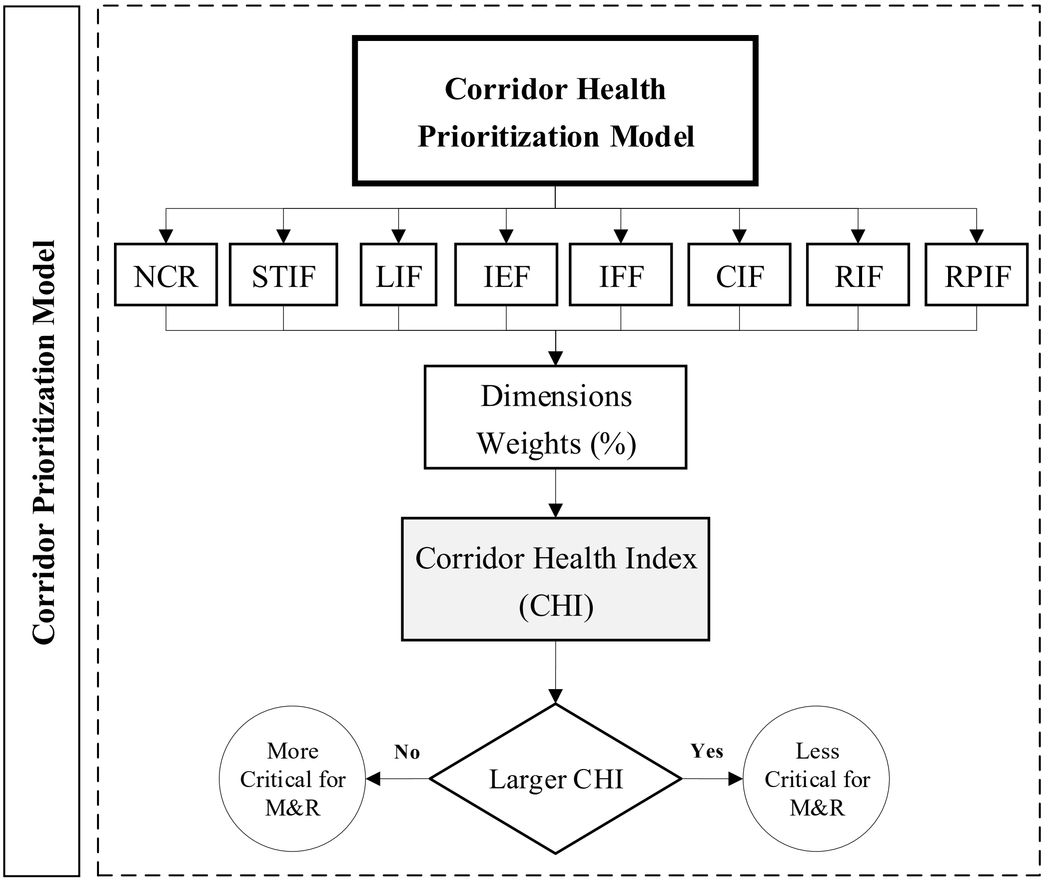


Figure 3.21: *Corridor health prioritization model flowchart*

Table 3-19: *Assessment indicators' weights of importance*

Performance Indicator	Basis	Weights of importance (%)	Illustrative Example
Time	Intervention Duration	10%	Critical areas (i.e. commercial areas)
Space	Intervention Spatial and Interdependency	10%	Critical areas (i.e. commercial areas)
Cost	Life-Cycle Costs	20%	Tough budgetary constraints
Efficiency	Intervention Crew	5%	Low intervention crew productivity issues
Effectiveness	Intervention Quality	5%	Low intervention quality and more frequent issues

Performance Indicator	Basis	Weights of importance (%)	Illustrative Example
Condition	Physical state, Reliability, and LOS	20%	Higher LOS (i.e. water and sewer mains; large pipes beside the water or sewer treatment plants, arterial roads, etc.)
Resilience Preparedness	Demand and supply theory	10%	Steep demand increasing area (i.e. land-use change from residential to industrial [water pipes], increasing rainfall frequency and intensity due to climate change [combined sewer and stormwater pipes], etc.)
Risk	Probability and Consequences of Failure	20%	Critical area (i.e. mixed residential and commercial uses, industrial areas)

Hence after, the Corridor Health Index (CHI) is calculated, as shown in Equation 3.76. A weighted sum method has been used to integrate all the factors (KPIs) together in one indicator that reflects the vision of the management and comes up with an intervention plan that fits the municipality priorities and preferences. As mentioned earlier, the weights vary from one corridor to another and among different stakeholders. Moreover, the scores of each factor are determined based on the previously-developed models to reflect the percentage of compliance with the pre-defined thresholds (i.e. LCC should be less than the available budget, condition should not be less than the contractual threshold, disruption in terms of time, space, and frequency should not exceed the thresholds to avoid extra indirect costs or contractual penalties, reliability should be higher than the threshold to decrease the POF, etc.) Thus, the CHI is calculated for each corridor at a certain point of time (i.e. end of the planning horizon, annually, etc.) to display the overall health of the corridor. Hence, the asset managers will be able to visualize detailed information and trigger the main reason behind the low CHI. Furthermore, the model has identified five color codes to visualize the corridor health state, as shown in Figure **3.22**. Similarly, the Network Health Index (NHI) is calculated based on the corridor length and CHI, as shown in Equation 3.77. Finally, the average network length across the planning horizon could be computed as displayed in Equation 3.78.

$$CHI_{o_t} = \sum_f^F W_f * S_{f_o} \qquad (3.76)$$

$$\mathrm{NHI_t} = \sum_o^O \frac{L_o}{\sum_o^O L_o} * CHI_{o_t} \qquad (3.77)$$

$$\mathrm{NHI} = \overline{\mathrm{NHI_t}} \tag{3.78}$$

where CHI_{o_t} is the corridor health index of corridor *o* at point of time *t* (%); f is the counter of factors (number); F is the total number of factors (number); W_f is the weight of factor *f* (%); S_{f_o} is the score of factor *f* in corridor *o* (%); $\mathrm{NHI_t}$ is the network health index at point of time *t* (%); and L_o is the length of corridor *o* (m); and NHI and $\overline{\mathrm{NHI_t}}$ are the average network health index across the planning horizon (%).

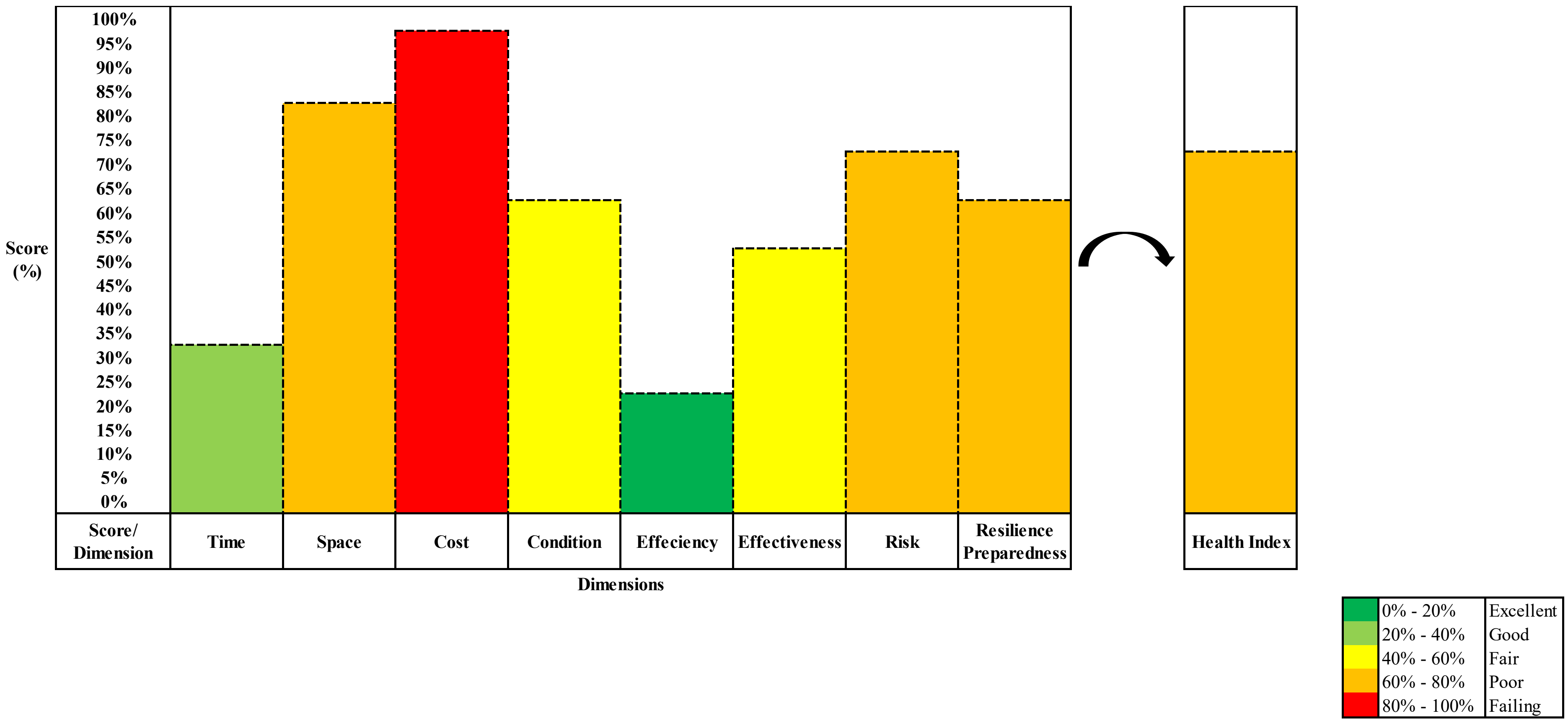


Figure 3.22: *Corridor health index visualization*

3.6 Optimization Models

The optimization models have been developed for both the pre-contract and post-contract phases, as shown in Figure 3.23. For the pre-contract, two scenarios have been established. The 1st scenario opts at defining the KPI thresholds that both aligns with the municipality goals and meets their limited resources (i.e. number of maintenance crews, annual budget, etc.). However, the 2nd scenario aims at minimizing the overall LCC through obtaining optimal P/I, given the pre-defined KPI thresholds, that aligns with the municipality goals within their limited resources. On the other hand, the post-contract optimization models target the maintenance contracts. It aims at coming up with an optimized intervention schedule that fits the pre-defined PBC parameters, minimizes their costs, and maximizes their profit. The optimization models were developed in two software packages: (1) spreadsheet modeling with GAs based optimization engine; and (2) REMSOFT software equipped with MOSEK linear and mixed-integer programming optimization algorithm. The optimization mathematical formulation is similar for both packages (REMSOFT 2018; MOSEK 2018). The only difference is the expanded capability of MOSEK linear and mixed-integer programming optimization algorithm over the GA such that it was applied to a greater number of corridors as opposed to the GAs spreadsheet model, which was very limited in terms of the number of corridors it could be potentially applied to. Accordingly, the model was applied to two case studies as will be discussed later in the next chapter: (1) city of Montreal; and (2) town of Kindersley. The city of Montréal system utilized spreadsheet modeling equipped with GAs optimization engine to solve 20 corridors (9 km). However, the town of Kindersley system utilized REMSOFT software equipped with MOSEK linear and mixed-integer programming optimization algorithm to solve 125 corridors (53 km), which is 6 times larger problem compared to the city of Montréal one. Details about the case studies will be discussed in the upcoming chapters. The mathematical formulation of the optimization models will be highlighted in the following sub-sections.

3.6.1 *Pre-Contract Phase*

The optimization model for the pre-contract phase could be set up into two different modes, as shown in Figure 3.23. The first mode is set up with an objective of minimizing the summation of the deviational variables, which are the PBC KPIs' thresholds, within the available budget and without reaching the unacceptable thresholds. The decision variables are the KPIs' threshold values, as displayed in Equation 3.79. The deviational variables' thresholds play an important role in the PBC as they define the expected KPIs' levels for all the n_s systems. Based on those thresholds, the maintenance contractors will compute the necessary intervention costs and consider unforeseen risks through a certain contingency (%), which varies according to numerous factors, but most importantly, the KPIs' thresholds and the contractual P/I. Accordingly, it is necessary to balance the trade-off between the end users, who are the definite target of the expected KPIs' levels, and the maintenance contractors, who are the budget users. In other words, the municipalities have to undertake a trade-off analysis between the KPIs' levels and cost. The key question, in this case, should be "Are the end users willing to pay extra premium/money to elevate the KPIs' levels (i.e. increase LOS, reliability, etc.). Non-preemptive goal optimization was used to solve the problem. The optimization mathematical formulation could be summarized in Equations 3.81, 3.82, 3.83, 3.84, 3.85, 3.86, 3.87, and 3.88. The objective function is minimizing the deviational variables from the KPI's thresholds, as shown in Equation 3.81. The constraints are modeled through binary coding rules, such that "0" implies that the constraint threshold has been met and "1" implies that the constraint threshold has not been met. The model constraints are as follows: (1) financial resources (budget); (2) maintenance capacity; (3) number of annual intervention activities; (4) temporal limit; (5) demand/capacity ratio; and (6) spatial disruption (i.e. lane rental approach). Aside from that, the optimization model can be set up in another mode to solve another scenario and obtain an optimal set of P/I that guarantees the successful delivery of the KPIs without an elevated contingency (%), which might be placed by the maintenance contractors because of the improper risk allocation and high penalties. Hence, the objective and constraints formulation will be similar to the previous scenario, as displayed in Equations 3.80, 3.81, 3.82, 3.83, 3.84, 3.85, 3.86, 3.87, and 3.88. The deviational variables are computed through Equations 3.80 and 3.88. However, the decision variables will be the P/I for the pre-defined KPIs, as displayed in Equation 3.80. The P/I could be either monetary values that are incorporated in the financial model calculations or contractual period extension, which is incorporated through an extended planning horizon. The mathematical formulation of the financial penalties and incentives for corridor *o* at a certain point of time (*t*) could be displayed in Equations 3.89 and 3.90 respectively. The P/I system is integrated with the financial savings model as highlighted earlier in this chapter.

$$\textbf{Decision variables (Mode 1)} = \begin{bmatrix} TH_{v_i} & \cdots & TH_{v_{n_s}} \\ \vdots & \ddots & \vdots \\ TH_{V_i} & \cdots & TH_{V_{n_s}} \end{bmatrix} \tag{3.79}$$

For TH_{v_i} = 0, 1, … 100

v = 1, 2, … V

i = 1, 2, … n_s

$$\textbf{Decision variables (Mode 2)} = \left(\begin{bmatrix} P_{u_{v_i}} & \cdots & P_{u_{v_{n_s}}} \\ \vdots & \ddots & \vdots \\ P_{u_{V_i}} & \cdots & P_{u_{V_{n_s}}} \end{bmatrix} \cup \begin{bmatrix} I_{u_{v_i}} & \cdots & I_{u_{v_{n_s}}} \\ \vdots & \ddots & \vdots \\ I_{u_{V_i}} & \cdots & I_{u_{V_{n_s}}} \end{bmatrix} \right) \tag{3.80}$$

For P_{v_i} = 0, 1, … ($)

I_{v_i} = 0, 1, … ($)

v = 1, 2, … V

i = 1, 2, … n_s

$$\textbf{Min}(\mathbf{Z}) = \sum_{\mathrm{i}=1}^{n_s} \sum_{v=1}^{V} \sum_{\mathrm{t}=1}^{T} \left[\mathrm{W_i} * \mathrm{W_v} * (\mathrm{d}_{k\,t}^{-} + \mathrm{d}_{m\,t}^{+}) \right] \tag{3.81}$$

Subject to the following constraints:

$$\sum_{i=1}^{n_s} W_i = 1 \tag{3.82}$$

$$\sum_{v=1}^{V} W_v = 1 \tag{3.83}$$

$$LCC \leq \mathrm{LCC}_B \tag{3.84}$$

$$R_{i_{o_t}} \geq R_{th} \tag{3.85}$$

$$F_{i_{o_t}} \leq F_{TH} \tag{3.86}$$

$$\mathrm{d}_{k\,t}^{-} = \sum_{i=1}^{n_s} \sum_{h=1}^{H} \frac{KPI_{h_{i_t}} - TH_{h_i}}{TH_{h_i}}\ ; \textit{for all k and t} \tag{3.87}$$

$$\mathrm{d}_{m\,t}^{+} = \sum_{i=1}^{n_s} \sum_{l=1}^{L} \frac{TH_{l_i} - KPI_{l_{i_t}}}{TH_{l_i}}\ ; \textit{for all m and t} \tag{3.88}$$

$$P_{o_t} = \sum_{i=1}^{n_s} \sum_{\mathrm{v}=1}^{\mathrm{V}} \left(\mathrm{P}_{\mathrm{u}_{\mathrm{v}_i}} * \mathrm{PA}_{\mathrm{v}_{\mathrm{t}_i}} \right) ; \textit{for } KPI_{h_i} > TH_{h_i} \textit{or } KPI_{l_i} < TH_{l_i} \tag{3.89}$$

$$I_{o_t} = \sum_{i=1}^{n_s} \sum_{\mathrm{v}=1}^{\mathrm{V}} \left(\mathrm{I}_{\mathrm{u}_{\mathrm{v}_i}} * \mathrm{IA}_{\mathrm{v}_{\mathrm{t}_i}} \right) ; \textit{for } KPI_{h_i} \leq TH_{h_i} \textit{or } KPI_{l_i} \geq TH_{l_i} \tag{3.90}$$

where TH_{v_i} is the threshold values (decision variables for the 1st optimization mode) defined for each KPI (*v*) and system (*i*) (varies according to the KPI); $P_{u_{v_i}}$ is the financial penalty unit cost (decision variables for the 2nd optimization mode) defined for each KPI (*v*) and system (*i*) ($); $I_{u_{v_i}}$ is the incentive unit cost (decision variables for the 2nd optimization mode) defined for each KPI (*v*) and system (*i*) ($); Z is the summation of the deviational variables of n_s system throughout the planning horizon T (%); W_v represents the deferential weights among the conflicting goals (%); v is the KPIs' counter (number); V is the total number of KPIs (number); LCC_B is the available intervention budget across the planning horizon ($); C_{th} is the condition state threshold for all n_s systems (varies from one system to another) (%); $\mathrm{d}_{k_t}^-$ is the summation of all the negative deviational variables at point of time (t) (%); $\mathrm{d}_{m_t}^+$ is the summation of all the positive deviational variables at point of time (t) (%); h and l are the counters of the positive and negative deviational variables respectively (number); H and L are the total number of positive and negative deviational variables respectively (number); KPI_{h_i} and KPI_{l_i} are the values of positive KPI (*h*) and negative KPI (*l*) respectively for system (*i*) at the time of assessment (*t*) (varies according to the KPI); TH_{h_i} and TH_{l_i} are the KPIs' threshold values of the positive KPI (*h*) and negative KPI (*l*) respectively for system *i* (varies according to the KPI); $\mathrm{PA}_{\mathrm{v}_{\mathrm{t}_i}}$ is a binary financial penalty applicability index for KPI (*v*) at time (*t*) for system (*i*) (0 or 1); and $\mathrm{IA}_{\mathrm{v}_{\mathrm{t}_i}}$ is a binary financial incentive applicability index for KPI (*v*) at time (*t*) for system (*i*) (0 or 1).

3.6.2 *Post-Contract Phase*

The need for optimization was obvious due to the numerous possible and valid alternatives (i.e. intervention decisions). For instance, the number of solutions for 20 corridors for one system only, across 25 years planning horizon, incorporating five maintenance actions is 5^{20*25}. Furthermore, the limited budget and increasing demand for higher LOS placed extra pressure on the asset managers to "optimally" utilize their expenditure and fulfill the end users' expectations within the tight available budgets. Moreover, the lengthy planning horizon (i.e. 25 years) even made it more computationally complicated and challenging, setting extra uncertainty for asset managers while taking intervention decisions. Thus, three optimization techniques were set up for the post-contract phase, as shown in Figure 3.24, Figure **3.25**, and Figure 3.26: (1) single objective; (2) non-preemptive goal optimization; and (3) multi-objective hierarchical goal optimization. The explanation of each technique along with its mathematical formulation will be thoroughly discussed in the following sub-sections.

3.6.2.1 *Single objective*

The single objective formulation opts at maximizing the NHI while meeting the contractual KPIs' thresholds. To solve the problem in hand, GAs engine combined with pre-applied meta-heuristic rules, which minimize the optimization engine search space, were applied. GAs is derived from the biological systems. It relies on simulating the natural survival of the fittest where the solution is represented as a string of chromosomes, which consist of several genes. The genes' exchanging process within the chromosomes is carried out through mutation and crossover operations and new solutions are evaluated to replace the weaker member in the population and produce better solutions. This process continues until a near-optimum solution is generated. The GAs performance is affected by four main parameters: (1) number of generations; (2) population size; (3) mutation rate; and (4) crossover rate (Elbeltagi and Tantawy 2008). The system utilized advanced spreadsheet modeling and Evolver™ Version 7.0 as an optimization engine (Palisade 2016). It functions through a powerful engine that is designed to fit the municipalities' needs and meet the KPIs' defined thresholds. To reduce the search space, several pre-determined metaheuristic rules are applied as follows: (1) number of annual intervention actions; (2) corridor-based inter-disruption time between carrying out one intervention action and another to minimize the service disruptions; and (3) number of corridor interventions across the planning horizon. The decision variables are formulated through integer programming, where the decision variables ranges are defined according to the number of intervention activities that need to be addressed in the model. The wider the range of the decision variables, the exponentially more computationally complicated the optimization problem is, as it generates a greater spectrum of possible combinations and requires an evolutionary optimization algorithm to reach a near-optimum solution for this combinatorial-in-nature problem. In this problem, the decision variables vary between 0 and 10, as shown in the action level decision variables of Table 3-20. Hence after, the constraint check is undertaken annually and uses binary coding rules, where "0" represents meeting the constraint and "1" represents the failure to meet the constraint, to guarantee that the KPIs are met on an annual basis. The mathematical formulation of the single objective optimization problem is shown in the equations below.

$$\textbf{Decision variables} = \begin{bmatrix} I_{t_O} & \cdots & I_{T_O} \\ \vdots & \ddots & \vdots \\ I_{t_O} & \cdots & I_{T_O} \end{bmatrix} \tag{3.91}$$

For I_{t_O} = 0, 1, … 10

t = 1, 2, … T

o = 1, 2, … O

$$\boldsymbol{Max}(\textbf{NHI}) = \sum_{o=1}^{O}\left(\frac{L_o}{\sum_{o=1}^{O} L_o} * CHI_{o_t}\right) \tag{3.92}$$

Subject to the following constraints:

$$LCC \leq \mathrm{LCC}_B \tag{3.93}$$

$$CCD_t \leq D_a \tag{3.94}$$

$$IN_t \leq IN_a \tag{3.95}$$

$$R_{i_{o_t}} \geq R_{th} \tag{3.96}$$

$$F_{i_{o_t}} \leq F_{TH} \tag{3.97}$$

$$RI_{o_t} \leq RI_{th} \tag{3.98}$$

where D_a is the available duration based on the maintenance capacity (hours); IN_t is the number of annual interventions at a certain point of time (t) (number); IN_a is the allowable number of annual interventions to avoid extra disruption for the surrounding community (number); and RI_{th} is the RI threshold (0-5).

3.6.2.2 *Non-preemptive goal optimization*

The non-preemptive goal optimization model differs from the single objective as it accounts for all the KPIs while undertaking intervention decisions. Similar to the single objective, integrated goal optimization and GAs combined with pre-applied meta-heuristic rules, which minimize the optimization engine search space, were applied. The decision variables formulation takes place through integer programming where the variables formulation could be summarized as follows: (1) "0" represents the "Do nothing" and the "road maintenance" scenarios where either no maintenance took place at this point of time or only road maintenance took place. This road maintenance was combined with the "Do nothing" scenario as there is only a one-way functional interdependency where a disruption caused by the road will neither affect the water or sewer networks. (2) "1 and 2" represent the "only water or sewer rehabilitation" scenario where either the water or sewer network is undergoing an intervention and the road is not. In this case, the geographical interdependency takes place, as the two assets are geographically located at the same space and the disruption of the water network will partially/fully affect the road service. In addition, the maintenance of the water network requires excavating the corridor, which implies applying a "reconstruction" for the road corridor and returning it to a pristine condition state. (3) "3, 4, and 5" represent the "partially-coordinated" scenario where the intervention actions are partially-coordinated for either the roads and water networks, or roads and sewer networks, or water and sewer networks respectively. In this case, the road network will undertake a "reconstruction" given the fact that it will be impossible to carry out “slurry seal” or “crack filling” when you are rehabilitating/replacing the water network, and (4) “6” represents the “fully-coordinated” scenario where the roads, water, and sewer networks’ interventions are fully-coordinated. The wider the range of the defined decision variables, the exponentially more complicated the optimization problem is, generating a greater spectrum of possible combinations and requiring an evolutionary optimization algorithm to reach a near-optimum solution for the combinatorial-in-nature problem. Hence after, dynamic programming has been utilized due to the complexity of the optimization problem and the lengthy planning horizon. Thus, 5-years segmentation analysis was chosen for applying dynamic programming and the optimization has been subsequently done across the whole planning horizon in a chronological sequence. Goal programming or goal optimization has been chosen for the problem in hand, given the fact that the problem features conflicting goals and multiple assets. The objective is linked to the variables through “Goal Constraints”. However, the objective is clearly formulated to minimize the sum of deviations for the prescribed goal values defined by the user. To combine the objectives, a percentile ranking approach was utilized by calculating the percentage deviation from a goal rather than the absolute deviation (Schniederjans 1995). Finally, the deviational variables are formulated to fit the pre-defined set of KPIs, as shown in the aforementioned equations.

$$\mathbf{Min}(\mathbf{Z}) = \sum_{\mathrm{i}=1}^{n_s} \sum_{v=1}^{V} \sum_{\mathrm{t}=1}^{T} \left[\mathrm{W_i} * \mathrm{W_v} * (\mathrm{d}_{k\,t}^{-} + \mathrm{d}_{mt}^{+})\right] \tag{3.99}$$

Subject to the following constraints:

$$\sum_{i=1}^{n_s} W_i = 1 \tag{3.100}$$

$$\sum_{v=1}^{V} W_v = 1 \tag{3.101}$$

$$LCC \leq \mathrm{LCC}_B \tag{3.102}$$

$$CCD_t \leq D_a \tag{3.103}$$

$$IN_t \leq IN_a \tag{3.104}$$

$$R_{i_{o_t}} \geq R_{th} \tag{3.105}$$

$$F_{i_{o_t}} \leq F_{TH} \tag{3.106}$$

$$RI_{o_t} \leq RI_{th} \tag{3.107}$$

3.6.2.3 *Multi-objective hierarchical goal optimization*

The complexity of the problem on hand arises from the spatial interdependency among the assets under study as well as the varying intervention scenarios. Thus, it would be computationally impossible to manually reach an optimal solution due to the outsized search space. The scenario of "n_s" systems, "o" corridors, "t" planning horizon, and "c" coordination scenarios will yield a total of c^{ns*o*t} possible solutions. Even though previous scholars utilized dynamic programming and phased optimization for fund allocation problems (Atef *et al.* 2012; Atef and Moselhi 2013a; 2013b; Hegazy and Elhakeem 2011; Scheinberg and Anastasopoulos 2009), they result in near-optimal solutions, based on a micro-level, which are not necessarily optimal for the macro-level problem on hand. The fact that it disables the decision-makers to "*see the forest for the trees*" might impact their outcome and result in sub-optimal solutions (Colson *et al.* 2007). Thus, the proposed integrated non-preemptive, multi-objective hierarchical goal optimization and GAs or MOSEK approach opts at attaining an optimum or near-optimum solution for n_s systems in "o" corridors to reach a globally optimal solution for the overall network. It functions through eight integrated models that compute the duration, cost, space utilized, efficiency, effectiveness, condition, resilience preparedness, and risk of each corridor, accounting for all the possible combinations. Thenceforth, the decision-making is undertaken through three layers where two of them are inner layers that act as an output of the outer optimization problem, as shown in Figure 3.27. Those layers represent the hierarchical levels where the outer layer represents the coordination level decisions; the inner layers represent the systems and actions levels' decisions respectively. As shown in Figure 3.27, the outer optimization layer, decision-making layer, aims at taking coordination decisions on a network level. In this level, the model answers two questions. The 1st one is "should we undertake an intervention for this corridor?", and if the answer is yes, the 2nd questions is "how many systems should undertake interventions at this point in time?". The answers to those questions are then processed within the two inner layers. The 1st inner layer, systems layer, deals with each system within each corridor separately. Based on the health of each system within the corridor, the model aims at answering one question that is "which system(s) need intervention(s)?". For instance, if the answers of the outer layer were "yes for corridor 2" and "two in the 2nd year", the model will select the two systems with the least condition out of the n_s systems for interventions. Thus, in the case shown in Figure 3.27, the model selected system i and i+1 for intervention, given that they have the least condition and the outer optimization layer selected 2 systems "partial combination". Finally, the 2nd inner layer, actions layer, deals with the intervention actions along with their associated costs, duration, risk, resilience and condition improvement. Based on the answer of the predecessor layer's question, the model will answer one question that is "what type of intervention is required to enhance the system condition/resilience state within the least cost, duration?". For instance, let's continue the previous case of corridor 2 where the model selected system i and i+1 for interventions. In this case, the 2nd inner layer selects the suitable intervention type (i.e. minor or major) for this corridor, based on the weights of importance associated with the conflicting objectives. If the municipality has a limited budget, the model will select the alternative with minimum cost to meet their tight budget. Similarly, if the municipality is looking for a better LOS, the model will select the alternative that best enhances the system condition state and LOS accordingly. The outcome of the 2nd inner layer directly feeds the objective with the financial, temporal, condition, spatial, efficiency, risk, resilience preparedness, and effectiveness improvement information of the intervention scenario for all the corridors in the network under study.

This newly developed multi-objective hierarchical optimization approach drastically reduced the search space through removing the illogical solutions (i.e. undertake a pipe replacement for a newly installed pipe, do resurfacing for a newly constructed road, etc.). To better imagine the huge savings in the computational time, let's assume a case of 20 corridors, with 3 systems in each corridor, 2 intervention types for each system (minor and major), and 25 years planning horizon. In typical one-level decision-making, the number of decision variables will range from 0 (Do nothing) to 10 to account for all the coordination scenarios, systems and their corresponding types of interventions. Thus, the number of possible solutions will be 11^{20*25}. In the multi-objective hierarchical decision-making, the decision variables will range from 0 (Do nothing) to 3 (number of systems per intervention). In that case, the number of possible solutions will be 4^{20*25}. The reduction of the search space, represented through savings in the number possible solutions, for the hierarchical approach would be the difference between both approaches, which is 7^{20*25}, almost three times less number of possible solutions, compared to the one-level decision-making. Moreover, given the complexity of the problem in hand, integrated goal optimization, integer programming, and GAs or MOSEK were utilized to enable decision-makers trade-off their interventions based on conflicting goals as displayed in the equations below. The $s_{o_{tcir}}$ integer programming-based decision variable is used to represents the three-level dimensional space of "o" corridors, "t" planning horizon, "c" coordination scenario (i.e. conventional, partially-coordinated, or fully-coordinated), "i" system(s) selected for intervention, and "r" intervention type. The list of decision variables at each optimization layer is displayed in Table 3-20. For instance, if $s_{3_{52138}}$ is equal to 2, then corridor 3 at year 5 will experience a partial coordination for systems 1 and 3 using intervention 8. The model decision variables could be mathematically formulated as displayed in Equation 3.108. The model functions through one hard constraint to ensure proper condition state for all the n_s systems as displayed in Equations 3.110, 3.111, and 3.112.

The multi-objective optimization is beneficial for decision-makers having varying goal preferences. Those preferences might vary among different decision-making bodies such as; asset managers, maintenance contractors, citizens/users, politicians, etc. Accordingly, the multi-objective formulation accounts for all the decision-makers preferences through setting weights of importance for each one. It computes the improvement factor of each goal for each optimization scenario and compares it with the conventional scenario. Hence after, weighted-sum mean is used to combine multiple goals into a single function after assigning different weights of importance for each goal, which should sum up to 1 for all the goals/preferences. Each goal is formulated in the form of an improvement deviational variable (I_j) from the conventional scenario, as highlighted previously in the multi-dimensional performance assessment models. Finally, the objective function is formulated to maximize the overall improvements, resulting from the weighted-sum of the considered goals, as displayed in Equation 3.109.

$$\textbf{Decision variables} = \begin{bmatrix} s_{1_{1cir}} & \cdots & s_{O_{1cir}} \\ \vdots & \ddots & \vdots \\ s_{1_{Tcir}} & \cdots & s_{O_{Tcir}} \end{bmatrix} \tag{3.108}$$

For o = 1, 2, … O

t = 1, 2, … T

c = 1, 2, … n_s+1

i = 1, 2, … n_s

r = 1, 2, … R

$$\boldsymbol{Max}(\mathbf{G}) = \textstyle\sum_{u=1}^{U}\sum_{k=1}^{K}\sum_{m=1}^{M}\sum_{t=1}^{T}\left[\mathrm{W_u} * (\mathrm{I}^-_{\mathrm{k}_t} + \mathrm{I}^+_{\mathrm{m}_t})\right] \tag{3.109}$$

Subject to the following constraints:

$$\textstyle\sum_{u=1}^{U} W_u = 1 \tag{3.110}$$

$$CCS_{i_{SC_{o_p}}} \geq CCS_{i_{TH}} \tag{3.111}$$

$$F_{i_{o_t}} \leq F_{TH} \tag{3.112}$$

$$\mathrm{I}^{-}_{k\,t} = \sum_{i=1}^{n_s} \sum_{h=1}^{H} \frac{TH_{l_i} - KPI_{l_{i_t}}}{TH_{l_i}}\ ; \textit{for all k and t} \tag{3.113}$$

$$\mathrm{I}^{+}_{m_t} = \sum_{i=1}^{n_s} \sum_{l=1}^{L} \frac{KPI_{h_{i_t}} - TH_{h_i}}{TH_{h_i}}\ ; \textit{for all m and t} \tag{3.114}$$

where $s_{o_{tcir}}$ is an integer-programming-based decision variable that represents the three dimensional space of “o” corridors, “t” planning horizon, “c” coordination scenario, “i” system(s) selected for intervention, and “r” intervention type (number); R is the total number of intervention types available for each system i (number); *G* represents the maximized value for all the negative (I_k^-) and positive improvements (I_m^+) for U goals (%); *u* is the improvement deviational variables counter (number); *U* is the total number of improvement deviational variables (number); W_u represents the deferential weights among the conflicting goals (%); $\mathrm{I}^{-}_{k\,t}$ is the summation of all the negative improvement deviational variables at point of time (t) (%); ; $\mathrm{I}^{+}_{m_t}$ is the summation of all the positive improvement deviational variables at point of time (t) (%); h and l are the counters of the positive and negative improvement deviational variables respectively (number); H and L are the total number of positive and negative deviational variables respectively (number); $CCS_{i_{SC_{o_p}}}$ is the CCS of the resulting intervention scenario of system (i) within corridor o (%); and $CCS_{i_{TH}}$ is the CCS threshold for all n_s systems (varies from one system to another) (%).

Table 3-20: *Optimization decision-making levels and decision variables*

Coordination level (1)		System level (2)		Action level (3)	
Decision variable	**Description**	**Decision variable**	**Description**	**Decision variable**	**Description**
0	Do Nothing	*0*	Do Nothing	*0*	Do Nothing
1	Conventional (1 system)	*1*	Roads	*1*	Surface overlay
				2	Resurfacing
		2	Water	*3*	Leaks repair
				4	Pipe replacement
		3	Sewer	*5*	Leaks repair
				6	Pipe replacement
2	Partially-coordinated (2 systems)	*4*	Roads and Water	*7*	Pipe replacement and road resurfacing
		5	Roads and Sewer	*8*	Pipe replacement and road resurfacing
		6	Water and Sewer	*9*	Pipe replacement
3	Fully-coordinated (3 systems)	*7*	Full Coordination	*10*	Pipe replacement and road resurfacing

Outer optimization layer
(Decision-making layer)

Inner optimization layers

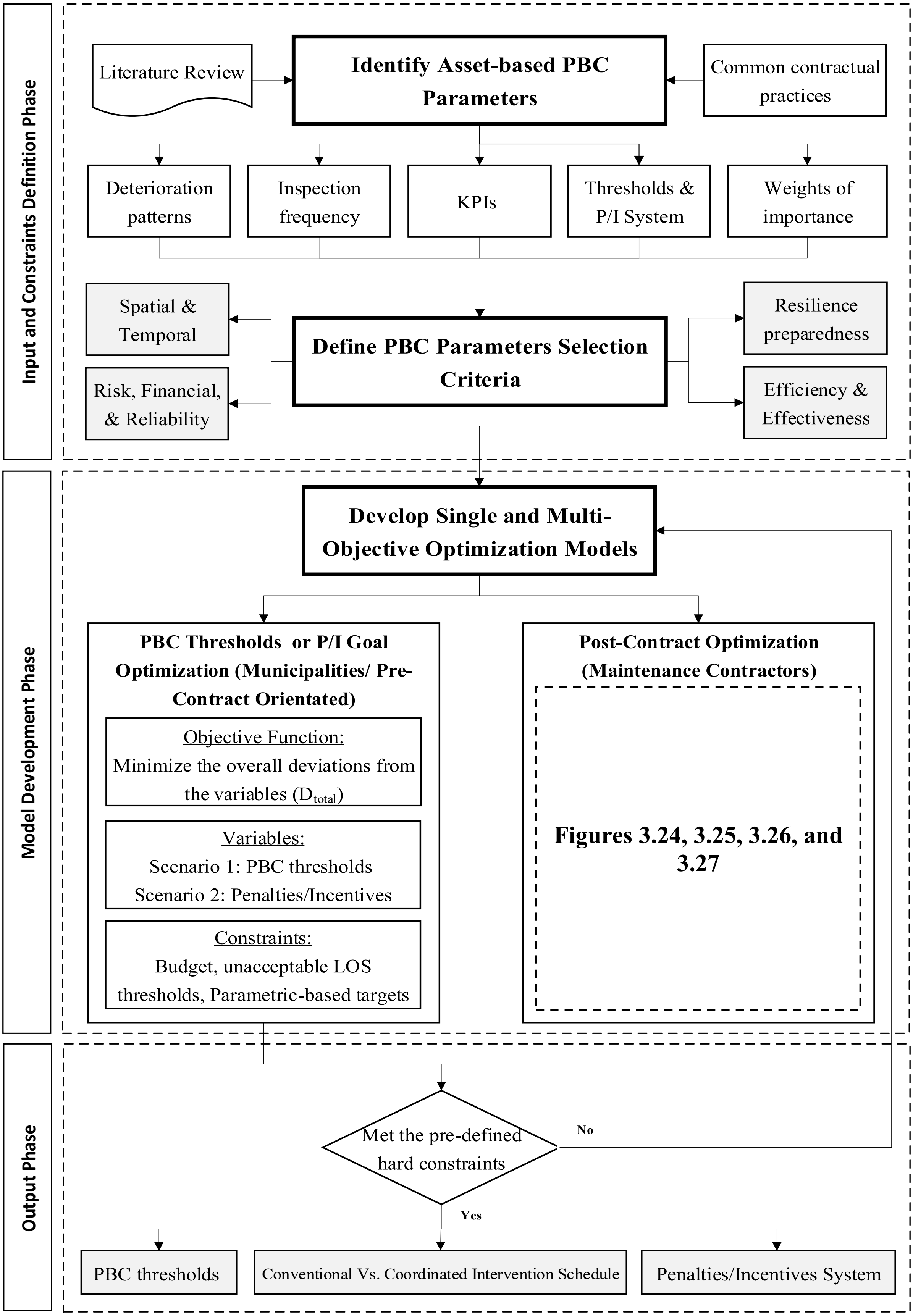


Figure 3.23: *Multi-objective PBC optimization flowchart*

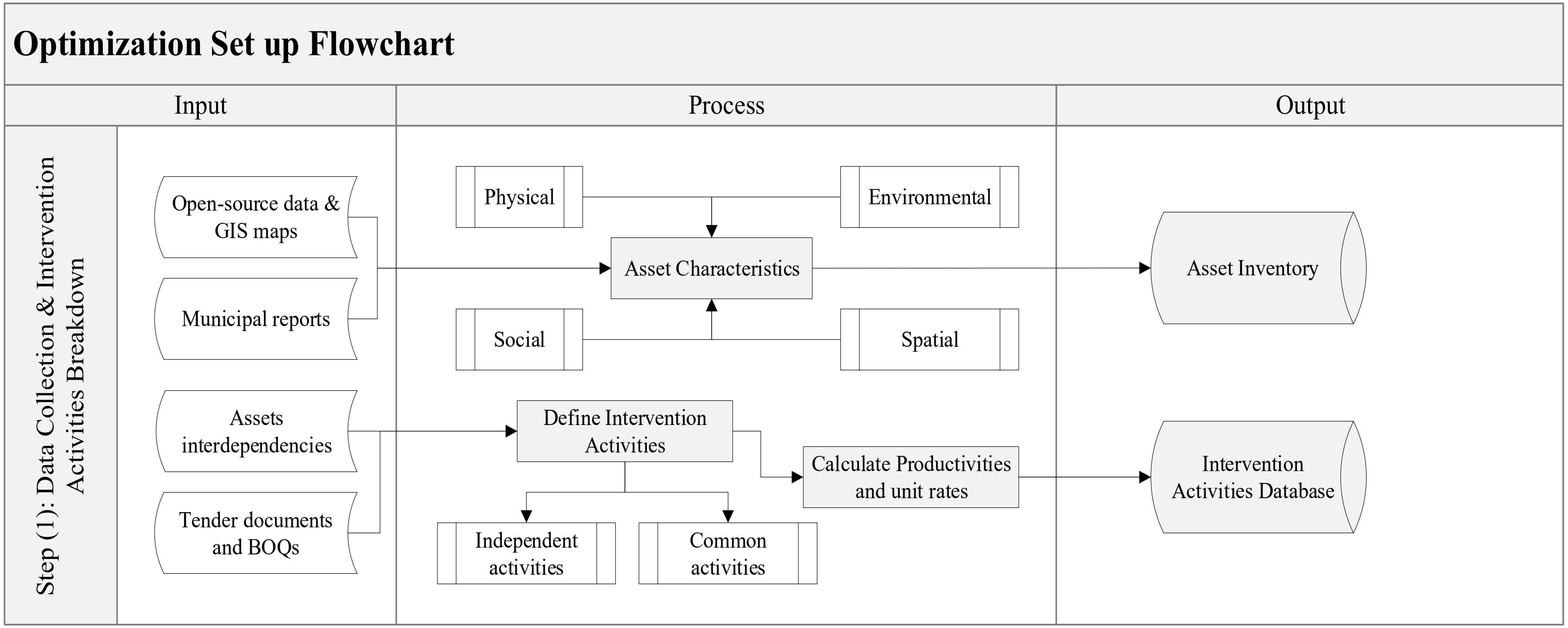


Figure 3.24: *Post-contract optimization flowchart (Data collection)*

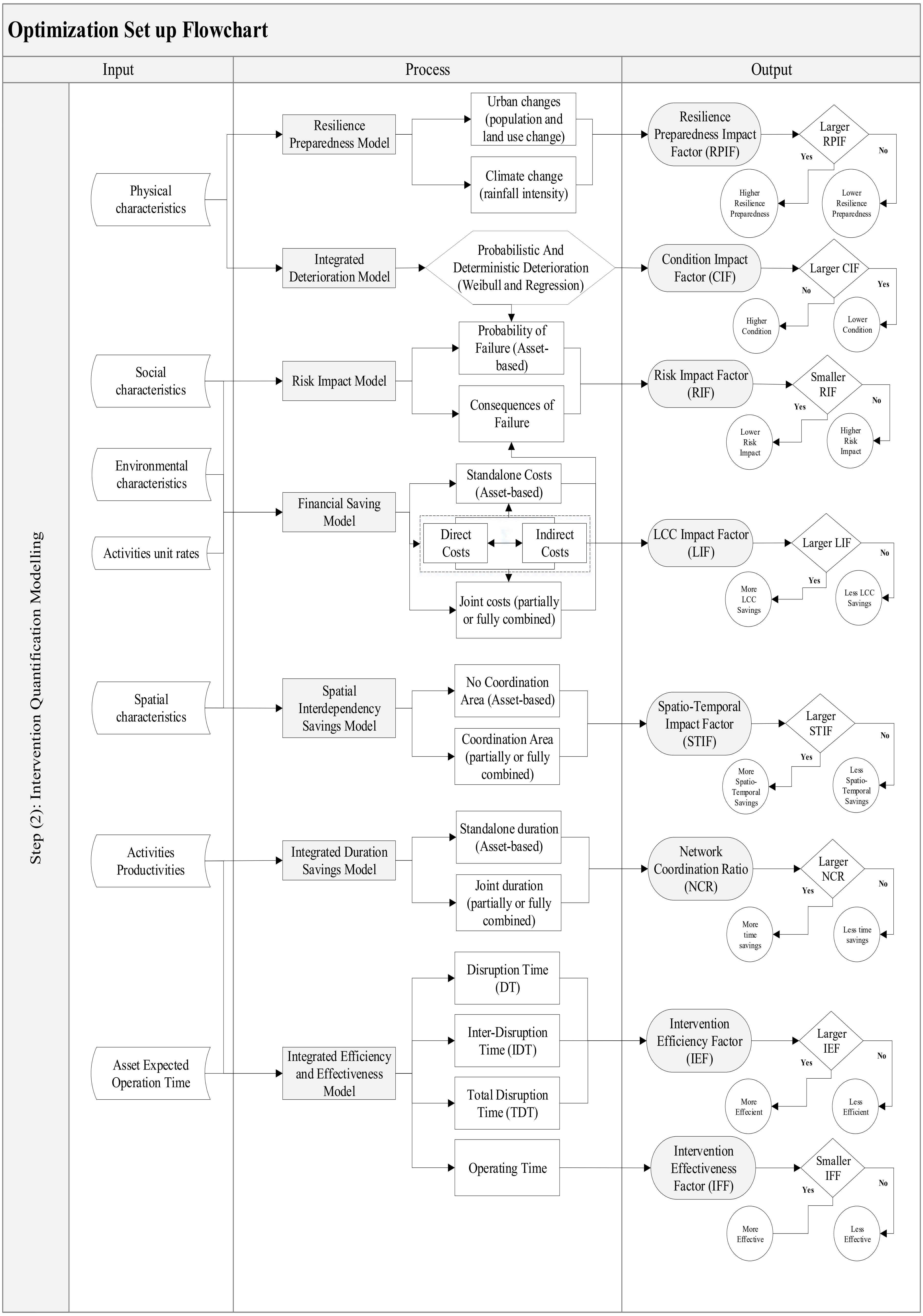


Figure 3.25: *Post-contract optimization flowchart (Intervention quantification models)*

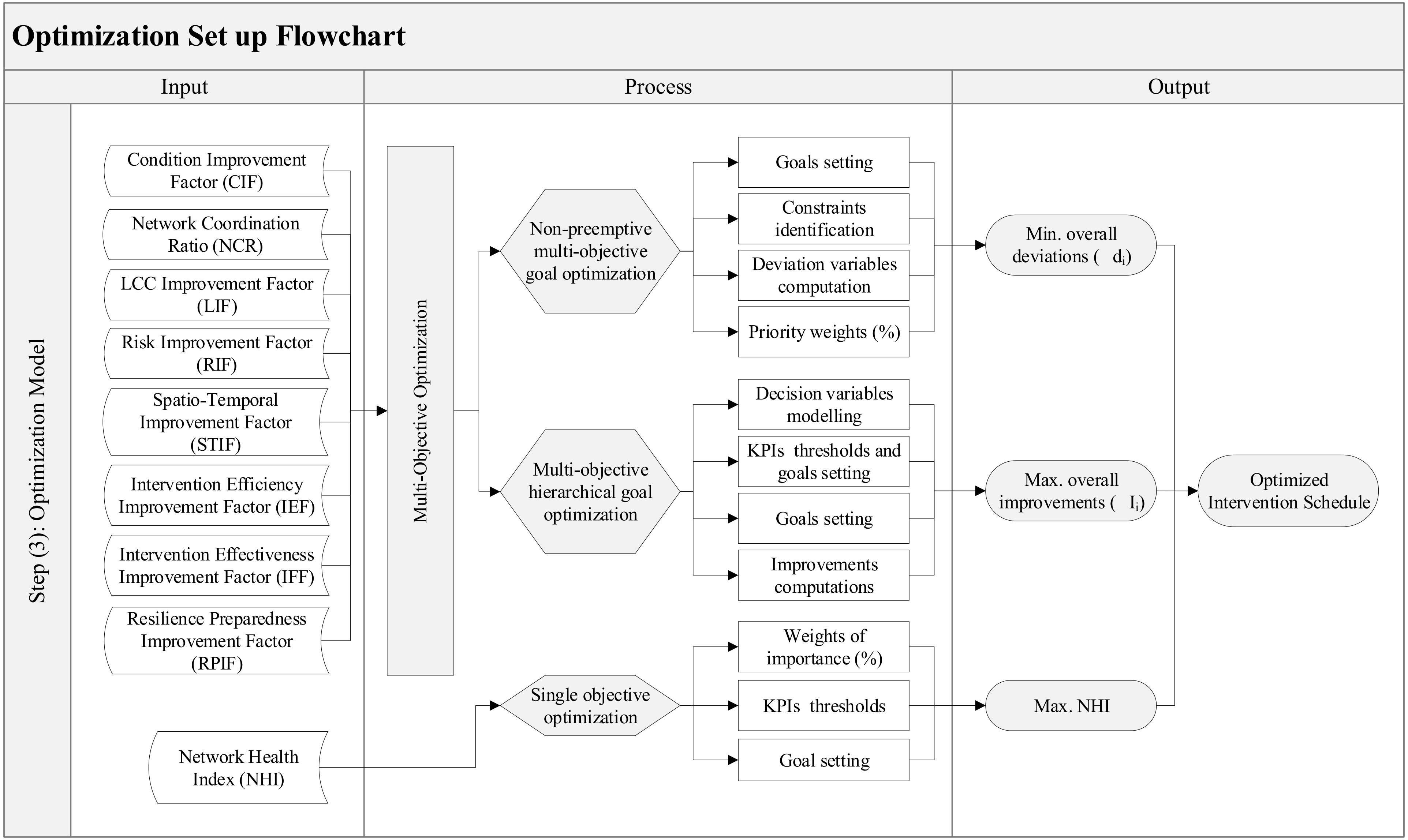


Figure 3.26: *Post-contract optimization flowchart (Optimization model)*

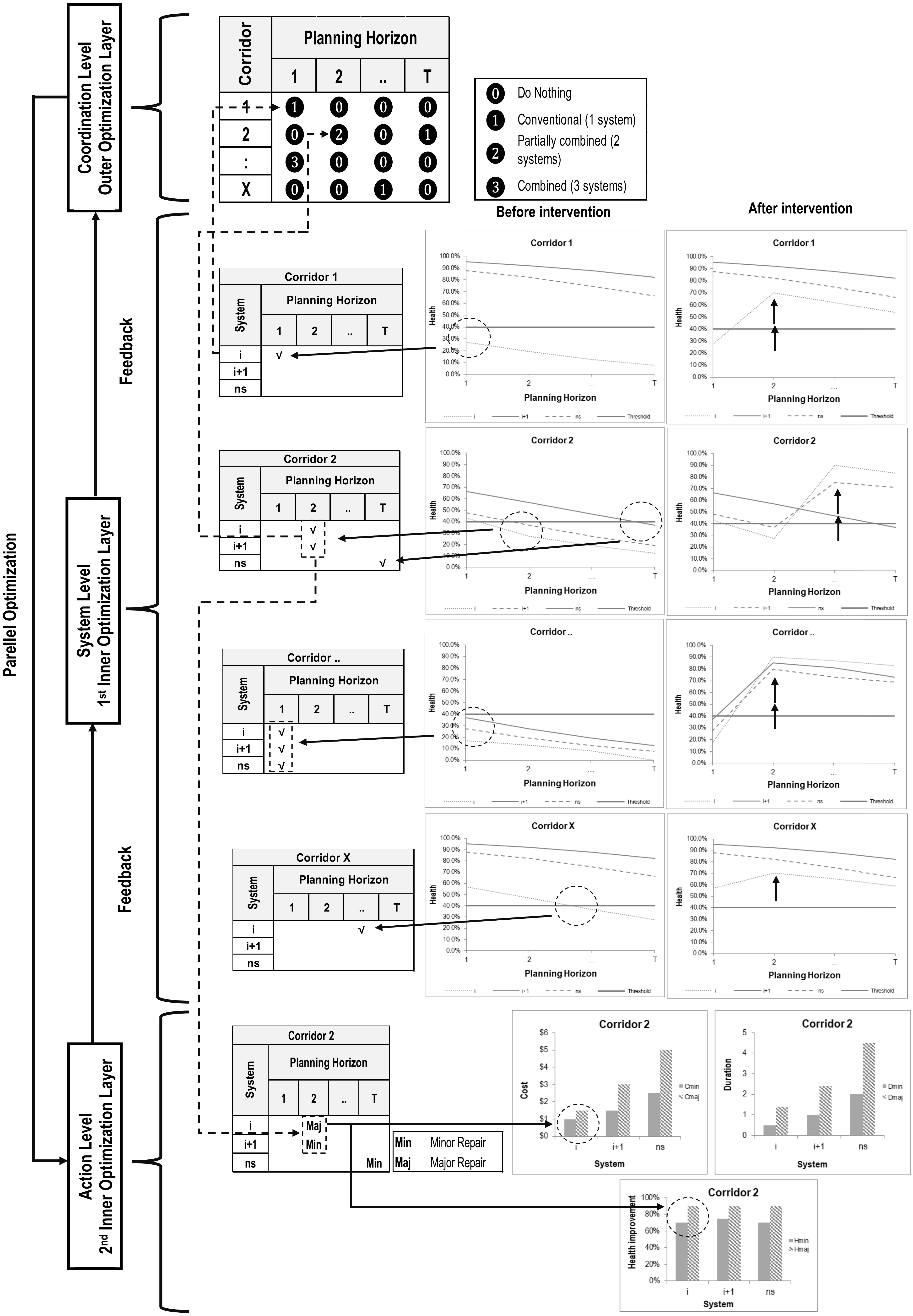


Figure 3.27: *Multi-objective hierarchical goal optimization model*

3.7 PBC-based Asset Management System

The PBC-based asset management system revolves through three core computational phases, as shown in Figure 3.28. The first phase is the central database, where four datasets are built as follows: (1) asset inventory where physical, spatial, social, and environmental characteristics of the systems under study are collected from various sources as will be highlighted on the data collection chapter, (2) intervention activities database, where intervention activities list and their associated unit costs and rates are identified from municipal data, tenders, as well as BOQs' as will be discussed in the next chapter. (3) KPIs' dataset, where the contractual KPIs along with their thresholds are identified, and (4) P/I dataset where the P/I of each KPI are identified along with application criteria (i.e. Roads reliability < 60 ➔ Penalty = 100 $/day, Corridor Health Index (CHI) > 70% for 5 years ➔ Incentive = 50 $/m/year, etc.). The second phase is the multi-dimensional performance assessment models. The multi-dimensional performance assessment models aim at computing the potential savings of coordinating the intervention activities of the co-located assets with the conventional intervention program. The model rests on eight dimensions as follows: (1) spatial, (2) temporal, (3) financial, (4) condition, (5) resilience preparedness, (6) risk, (7) efficiency dimension, and (8) effectiveness dimension. Finally, the optimization phase takes place in both pre-contract and post-contract phases. In the pre-contract phase, the optimization model aims at computing the optimal set of KPIs' thresholds and P/I to properly allocate the risks and minimize the contingency. For the post-contract phase, the optimization model aims at selecting the optimal intervention scenario for each corridor across the planning horizon. Since there are various conflicting objectives (i.e. minimize LCC, maximize CCS, etc.), a novel integrated hierarchical goal optimization and GAs or MOSEK was used to reduce the search space and reach a near-optimum solution for the conflicting objectives as highlighted earlier in this chapter. The optimization model is flexible to work on both the pre-contract and post-contract phases. Furthermore, it can serve both the municipalities and maintenance contractors to achieve their objectives. Finally, the model can be applied under the umbrella of PBC or in-house given the fact that the pre-defined KPIs are of importance for taking intervention decisions (i.e. the P/I can be set to "0" in case of in-house maintenance).

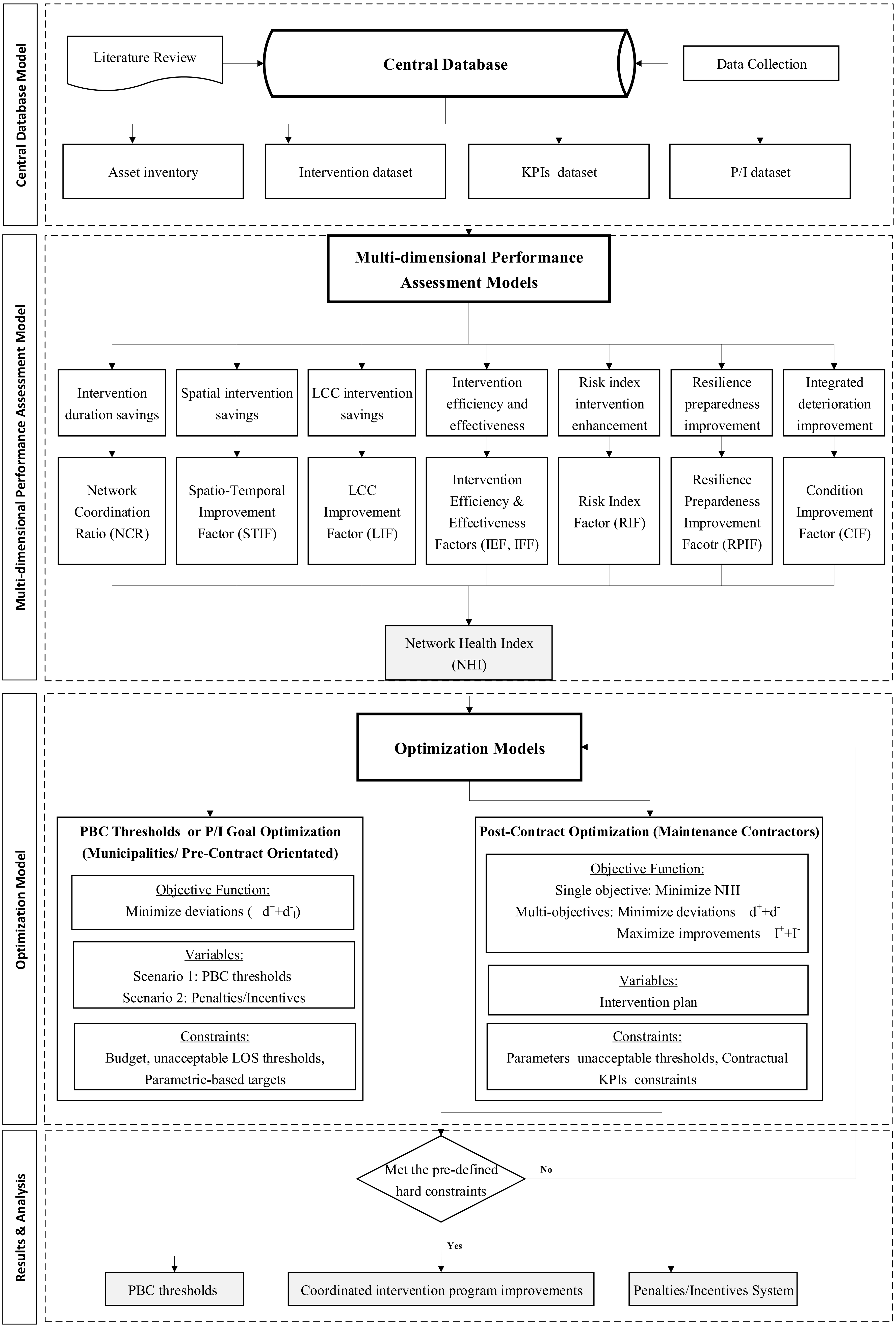


Figure 3.28: *PBC-based asset management system framework*

4 CHAPTER 4 - DATA COLLECTION AND PROCESSING

The previous chapter discussed the research methodology, as well as, the novel contractual scheme, multi-dimensional performance assessment models, and optimization models. This chapter aims at describing the data collection process. There are various types of data needed to fulfill the needs of the developed models and aid decision-makers in taking informed decisions. The data collection was conducted for the two case studies: (1) city of Montreal; and (2) town of Kindersley. The city of Montréal is in Quebec, Canada and the town of Kindersley is in Saskatchewan, Canada. The system was applied to a 9 km stretch in the city of Montreal. Thenceforth, the system capabilities were extended to 53 km stretch in the town of Kindersley, which was modeled on REMSOFT software package equipped with MOSEK linear optimization, which is a powerful large-scale sparse linear programming optimization algorithm. The corresponding information will be further discussed and analyzed in the following two sections.

4.1 City of Montréal Case Study

A 9 km stretch from the city of Montréal roads, water, and combined sewer networks was selected for the analysis. The network comprises 20 corridors and was equally divided into four areas with five corridors for each area. The dataset scale/size in terms of the number of corridors is scaled down several times to enable the use of the available optimization engines. It is worth noting that the condition states of the 20 corridors were assumed to represent the overall network condition states of each system. Time value of money was considered with an interest rate of 2% (Trading Economics 2017; Bank of Canada 2017). Furthermore, the study planning horizon was 25 years. The weights of the systems were assumed according to the overall LCC of each system across 100 years, using the longest life method. The results displayed 45%, 25%, and 30% for the roads, water, and sewer systems respectively. However, those weights are subject to change according to the stakeholders' preferences (i.e. condition, replacement cost, crews' availability, etc.). The physical and financial related data (i.e. physical state, operation and maintenance costs, water and sewer pipe breaks, etc.) was extracted from two sources: (1) interviews with city officials (Hachey 2017; Sabourin 2017); and (2) city of Montréal official website (Ville de Montréal 2017a; Ville de Montréal 2017b). The dataset was split into three categories for all the n_s systems. Each category comprises physical and financial data. Furthermore, Montréal's indicators were compared with other cities' indicators to display the performance difference and its' impact on the assets' physical and financial performance. Detailed discussion and analysis of the roads, water, and combined sewer networks data could be displayed in Appendix B.

4.1.1 *Asset Inventory*

The asset inventory contains all the assets that are spatially located in the same corridor. In this case study, 20 corridors were considered for the analysis as displayed in Table **4-1**. This information includes the corridor length, road width, number of lanes, area, average annual daily traffic, water or sewer pipe material and diameter, excavation depth, soil type, demand category, age/year or installation, etc. The asset inventory acts as a central database for the computational models such that all the necessary information about the corridor could be extracted directly from the inventory and used for further analysis.

4.1.2 *Temporal Dataset*

The temporal dataset includes all the information about the unit rates of different intervention actions and unit rate breakdown for each intervention activity. The unit rates have been adopted from the city of Montréal and the literature as displayed in Table 4-2 and Table 4-3 (Hachey 2017). It is worth noting that the temporal dataset is similar for both case studies. However, they differ in the number of corridors, current asset age, asset materials, pipe diameters', etc.

4.1.3 *Spatial Dataset*

Given the lack of available GIS combined dataset for the city of Montréal's roads, water, and combined sewer networks, the spatial dataset divided the corridors into four areas. Each area included five corridors such that the selected corridors are assumed to include the three assets spatially located. Furthermore, the area savings for the partial and fully-coordinated intervention scenarios as opposed to the conventional intervention scenario were computed for each corridor depending on several factors such as; road width, pipe diameter, excavation depth, intervention type, etc. Table 4-4 displays the % of area savings due to coordinating the intervention activities either partially or fully.

4.1.4 *Financial Dataset*

The financial dataset includes all the information about the costs of different intervention actions, cost breakdown for each intervention activity, indirect/user costs associated with disrupting the public, intervention cost in partial and full coordination scenarios. The costs have been adopted from the city of Montréal as well as several BOQs' as displayed in Table 4-5, Table **4-6**, and Table **4-7** (Ville de Montréal 2017a; Ville de Montréal 2017b; Forterra 2017; Qin and Cutler 2014; and TDOT 2016). It is worth noting that the financial dataset is similar for both case studies. However, they differ in the number of corridors, current asset age, asset materials, pipe diameters', etc.

4.1.5 *Physical Dataset*

The physical dataset includes all the information regarding the condition, age, physical characteristics, etc. The physical characteristics vary from one asset to another and even within the same asset. For instance, the roads' age could vary from 15 years to 25 years depending on the operational and climatic conditions, road design, sub-surface condition. Furthermore, the roads' deterioration pattern varies according to the expected service life of the asset, physical, operational, and climatic conditions (Abu-Samra *et al.* 2017). Thus, the models were classified into three categories based on the road structural design as well as the traffic: (1) low traffic; (2) medium traffic; and (3) high traffic (Amador and Magnuson 2011). The deterioration curve of each category could be displayed in Figure 4.1. For the water pipes, the age of the pipes varies from 60 years to 80 years according to the pipe material and diameter. Accordingly, the Weibull distribution will vary from one pipe to another according to its age as well as its associated shape (beta) and scale (alpha) parameters as highlighted earlier in the previous chapter. The pipe materials were classified to the following categories: (1) iron pipes that include cast iron and steel pipes; (2) plastic pipes that include PVC pipes; and (3) concrete pipes that include asbestos cement pipes and prestressed concrete pipes. The pipe diameters were classified to the following: (1) small pipes that include all the pipes with diameters less than 10 inches; (2) medium pipes that include all the pipes with diameters between 10 inches and 18 inches; and (3) large pipes that include all the pipes with diameters larger than 18 inches. According to those categories, different deterioration curves were developed with different ages, shape, and scale parameters. The deterioration curve of several pipe categories could be displayed in Figure 4.2. For the combined sewer and stormwater pipes, the age of the pipes varies from 80 years to 100 years according to the pipe material and diameter. Accordingly, the Weibull distribution will vary from one pipe to another according to its age as well as its associated shape (beta) and scale (alpha) parameters as highlighted earlier in the previous chapter. The pipe materials were classified to the following categories: (1) iron pipes that include corrugated steel pipes; (2) plastic pipes that include PVC pipes and vinyl pipes; and (3) concrete pipes that include asbestos cement pipes, prestressed concrete pipes, and vitrified clay pipes. The pipe diameters were classified to the following: (1) small pipes that include all the pipes with diameters less than 10 inches; (2) medium pipes that include all the pipes with diameters between 10 inches and 18 inches; and (3) large pipes that include all the pipes with diameters larger than 18 inches. According to those categories, different deterioration curves were developed with different ages, shape, and scale parameters. The deterioration curve of some pipe categories could be displayed in Figure 4.3. It is worth noting that the deterioration curves of both cases are similar. However, they differ in the number of corridors, current asset age, asset materials, pipe diameters', etc. Thus, the same deterioration curves for the different categories have been developed on the two modeling platforms.

4.1.6 *Resilience Preparedness Dataset*

Given the fact that demand curves were not available for the city of Montreal, the resilience preparedness model was excluded from the city of Montréal case study and was only applied to the town of Kindersley case study. Thus, details about the demand data for water and combined sewer and stormwater networks will be further discussed in the next section.

4.1.7 *Risk Dataset*

The risk dataset includes all the information about the POF and COF. For the POF, Table 4-8 was used to classify the POF for the roads, water, and combined sewer and stormwater networks. As highlighted earlier in the previous chapter, the POF of each asset was computed from the reliability using Equation 3.67. Thus, there are different POF curves for different assets and asset categories as displayed in Figure 4.4, Figure 4.5, and Figure 4.6 for roads, water, and combined sewer and stormwater assets respectively. Regarding the COF, the scoring ranges between 1 and 5 from insignificant to catastrophic respectively, as displayed in Table 4-9. Thus, according to the asset characteristics, the COF could be computed as detailed in the previous chapter. It is worth noting that the risk dataset is similar for both case studies. However, they differ in the number of corridors, current asset age, asset materials, pipe diameters', etc.

Table 4-1: *City of Montréal dataset*

General		Road Network						Water Network		Sewer Network	
Corridor ID #	**Corridor Length (m)**	**Number of Lanes**	**Lane Width (m)**	**Section Area (m²)**	**AADT**	**Traffic Growth Rate (%)**	**Current Condition (%)**	**Year of Installation**	**Pipe Diameter (cm)**	**Year of Installation**	**Pipe Diameter (cm)**
1	370	3	3	3,330	12,000	5%	90%	1953	450	1920	600
2	370	4	3	4,440	8,000	5%	70%	1982	150	1900	525
3	452	4	3	5,424	10,000	5%	85%	1976	250	1893	375
4	393	2	3	2,358	11,000	5%	65%	1958	200	1950	300
5	419	3	3	3,771	7,000	5%	70%	1965	150	1960	250
6	766	4	3	9,192	9,500	5%	90%	1991	100	1970	150
7	451	4	3	5,412	10,500	5%	70%	1992	500	1980	200
8	311	2	3	1,866	8,500	5%	85%	1977	500	1990	450
9	425	4	3	5,100	6,800	5%	65%	1982	350	2000	200
10	783	4	3	9,396	7,500	5%	70%	1991	500	1975	525
11	318	3	3	2,862	9,000	5%	90%	1972	500	1943	375
12	162	4	3	1,944	6,000	5%	70%	1960	250	1955	300
13	498	4	3	5,976	5,000	5%	85%	1979	250	1965	250
14	686	4	3	8,232	11,000	5%	65%	1953	100	1975	150
15	207	2	3	1,242	10,000	5%	70%	1960	450	1985	200
16	715	3	3	6,435	6,000	5%	90%	1977	200	1905	450
17	270	2	3	1,620	9,000	5%	70%	1986	150	1965	200
18	217	2	3	1,302	12,000	5%	85%	1992	350	1968	600
19	519	2	3	3,114	9,000	5%	65%	1975	300	1978	525
20	560	4	3	6,720	8,000	5%	70%	1987	150	1982	600

Table 4-2: *Water intervention repair time per street category per leak (Hachey 2017)*

Road Category	Repair Time (hours)
Local roads	4
Main roads	10
Arterial roads	16

Table 4-3: *Intervention activities unit rates (Hachey 2017)*

Intervention Activities	Unit	Unit Rate (hour/unit)
Site Reinstatement	m'	25
Joint Excavation and Shuttering	m^3	84.82
Sewer Excavation and Shuttering	m^3	84.82
Joint Backfilling and Compaction	m^3	19.22
Sewer Backfilling and Compaction	m^3	19.22
Reinstating Sewer Laterals	No.	6
Traffic Control Systems	day	13.77
Residents Notification	No.	250
Excavation of entrance and exit pits	m^3	60
Installation of sewer manholes	No.	10
Water Pipe Repair/Installation	m'	11
Sewer Pipe Repair/Installation	m'	12
Surface overlay	m^2	1
Road resurfacing	m^2	13
Water Pipe Bedding	m'	15
Sewer Pipe Bedding	m'	16
Water Main Pipe Leak Repair	leak	17
Sewer Main Pipe Leak Repair	leak	18
Water pipe installation (Trenchless)	m'	10
Sewer pipe installation (Trenchless)	m'	8

Table 4-4: *Area savings for different intervention coordination scenarios*

Corridor/Intervention Scenario	Conventional Intervention Scenario	Partially-coordinated Intervention Scenario	Fully-coordinated Intervention Scenario
Corridor 1	0%	20%	32%
Corridor 2	0%	23%	38%
Corridor 3	0%	14%	26%

Table 4-5: *Intervention activities unit costs*

Intervention Activities	Unit	Unit Cost ($/unit)
Site Reinstatement	m'	$660
Joint Excavation and Shuttering	m^3	$459
Sewer Excavation and Shuttering	m^3	$459
Joint Backfilling and Compaction	m^3	$303
Sewer Backfilling and Compaction	m^3	$303
Reinstating Sewer Laterals	No.	Varies**
Traffic Control Systems	day	$190
Residents Notification	No.	$3
Excavation of entrance and exit pits	m^3	Varies**
Installation of sewer manholes	No.	$950
Water Pipe Repair/Installation	m'	Varies**
Sewer Pipe Repair/Installation	m'	Varies**
Surface overlay	m^2	$25
Road resurfacing	m^2	$65
Water Pipe Bedding	m'	$157
Sewer Pipe Bedding	m'	$157
Water Main Pipe Leak Repair	leak	$825
Sewer Main Pipe Leak Repair	leak	$938
Water pipe installation (Trenchless)	m'	Varies**
Sewer pipe installation (Trenchless)	m'	Varies**

*Varies** represents a varying intervention unit cost depending on the pipe diameter and material*

Table 4-6: *Replacement rules and pipes' replacement costs (Forterra 2017)*

Original Pipe (mm)	Replacement Pipe (mm)			Unit Cost for same pipe size ($/m)				
	Low Demand	Medium Demand	High Demand	Pipe	E/B*	PR**	Installation	Total
300	375	450	600	$80.7	$65.0	$37.0	$225.0	$407.7
375	450	600	750	$99.6	$65.0	$37.0	$275.0	$476.6
450	600	675	900	$105.7	$65.0	$37.0	$300.0	$507.7
525	675	825	1050	$111.8	$65.0	$37.0	$325.0	$538.8
600	750	900	1200	$186.1	$65.0	$37.0	$366.7	$654.8
675		There is no pipe in this diameter		$260.3	$65.0	$37.0	$408.3	$770.6
750	900	1200	1500	$334.6	$65.0	$37.0	$450.0	$886.6
825		There is no pipe in this diameter		$378.9	$65.0	$37.0	$575.0	$1,055.9
900	1200	1350	1800	$423.3	$65.0	$37.0	$700.0	$1,225.3
1050		There is no pipe in this diameter		$544.8	$65.0	$37.0	$862.5	$1,509.3
1200	1500	1800	2400	$666.2	$65.0	$37.0	$1,025.0	$1,793.2
1350		There is no pipe in this diameter		$857.4	$65.0	$37.0	$1,237.5	$2,196.9
1500		There is no pipe in this diameter		$1,048.5	$65.0	$37.0	$1,450.0	$2,600.5
1800		There is no pipe in this diameter		$1,239.7	$65.0	$37.0	$1,662.5	$3,004.2
2400		There is no pipe in this diameter		$1,430.9	$65.0	$37.0	$1,875.0	$3,407.9

**E/B refers to the excavation and backfilling activities*

**PR refers to the pavement restoration activity ($/m ^{2})*

Table 4-7: *User costs (Qin and Cutler 2014; and TDOT 2016)*

Activities	Unit Cost ($/unit)
Passenger Cars	22.09
Trucks	32.26

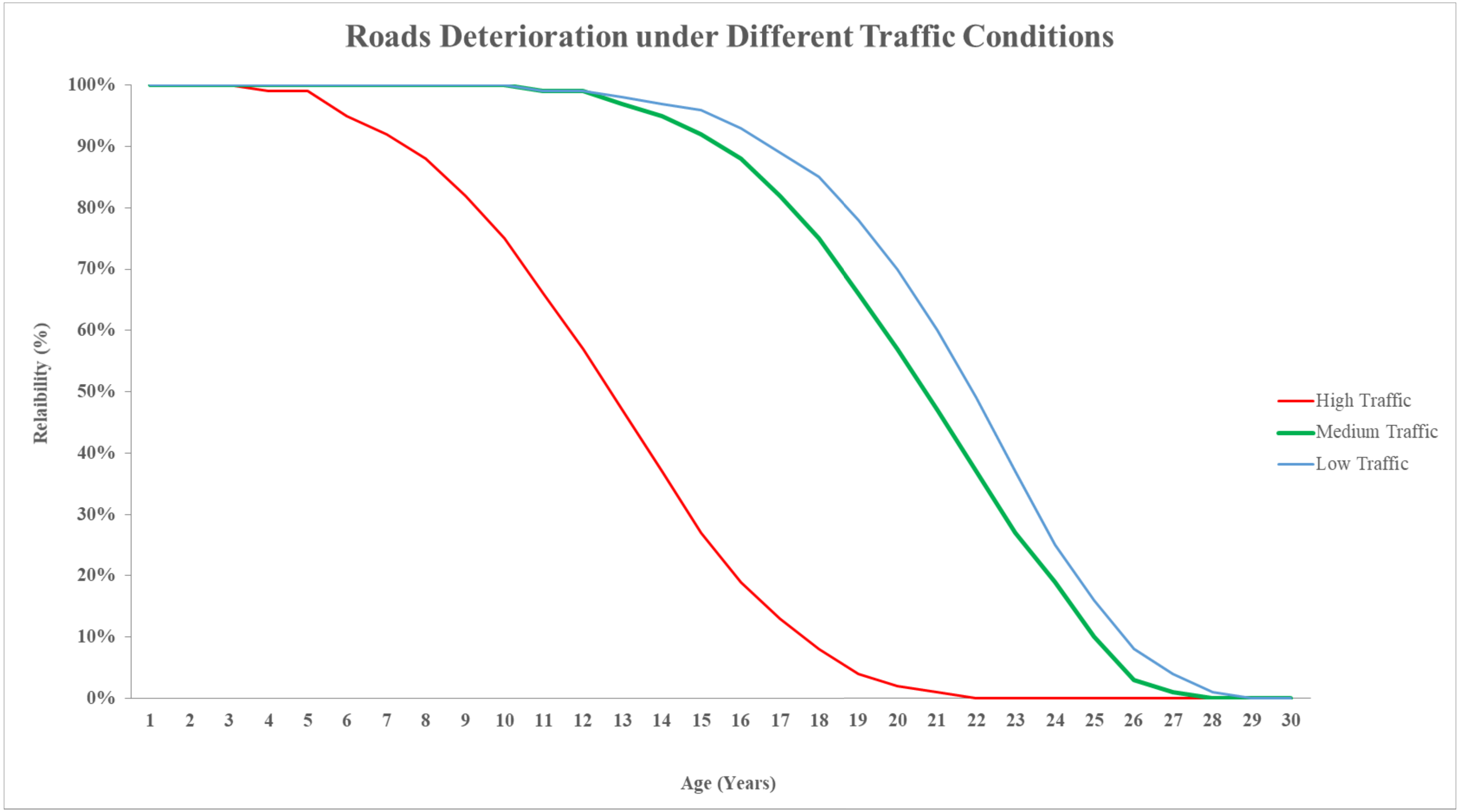


Figure 4.1: *Roads' deterioration under different traffic operational conditions*

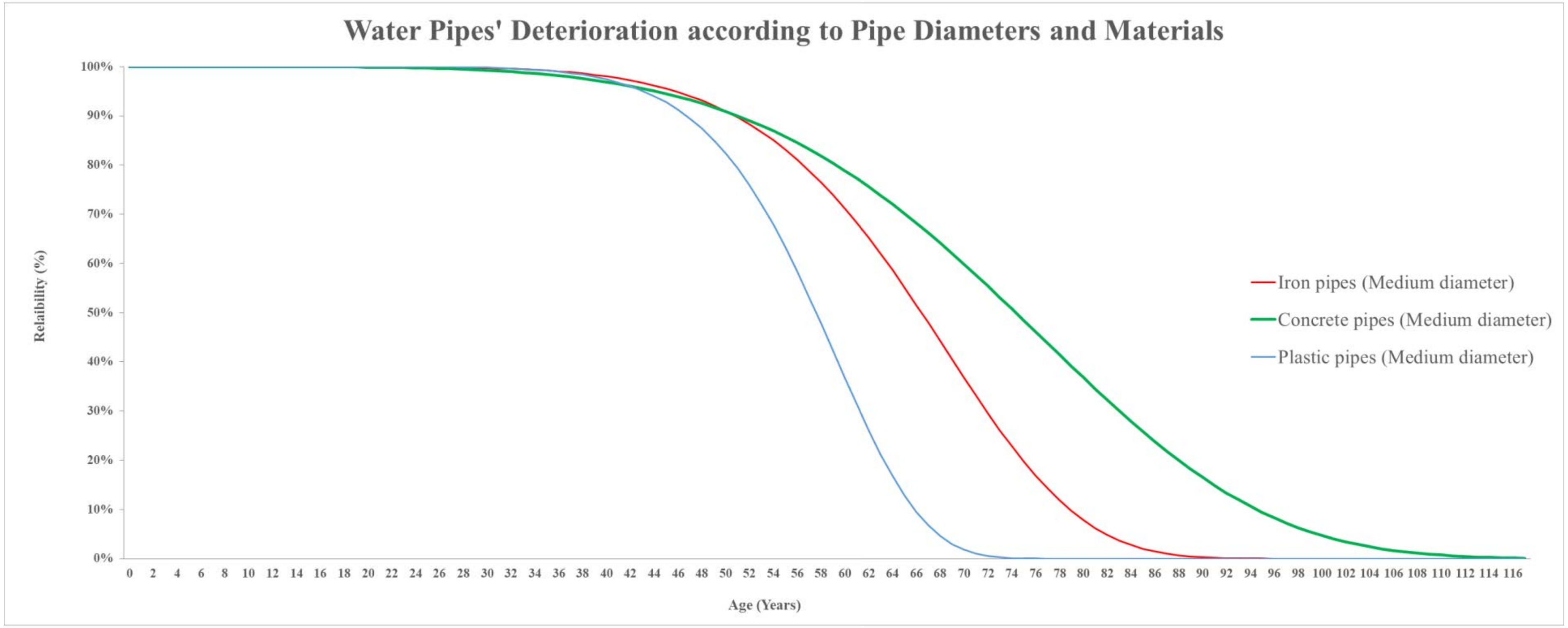


Figure 4.2: *Water pipes' deterioration according to different pipe diameters and materials*

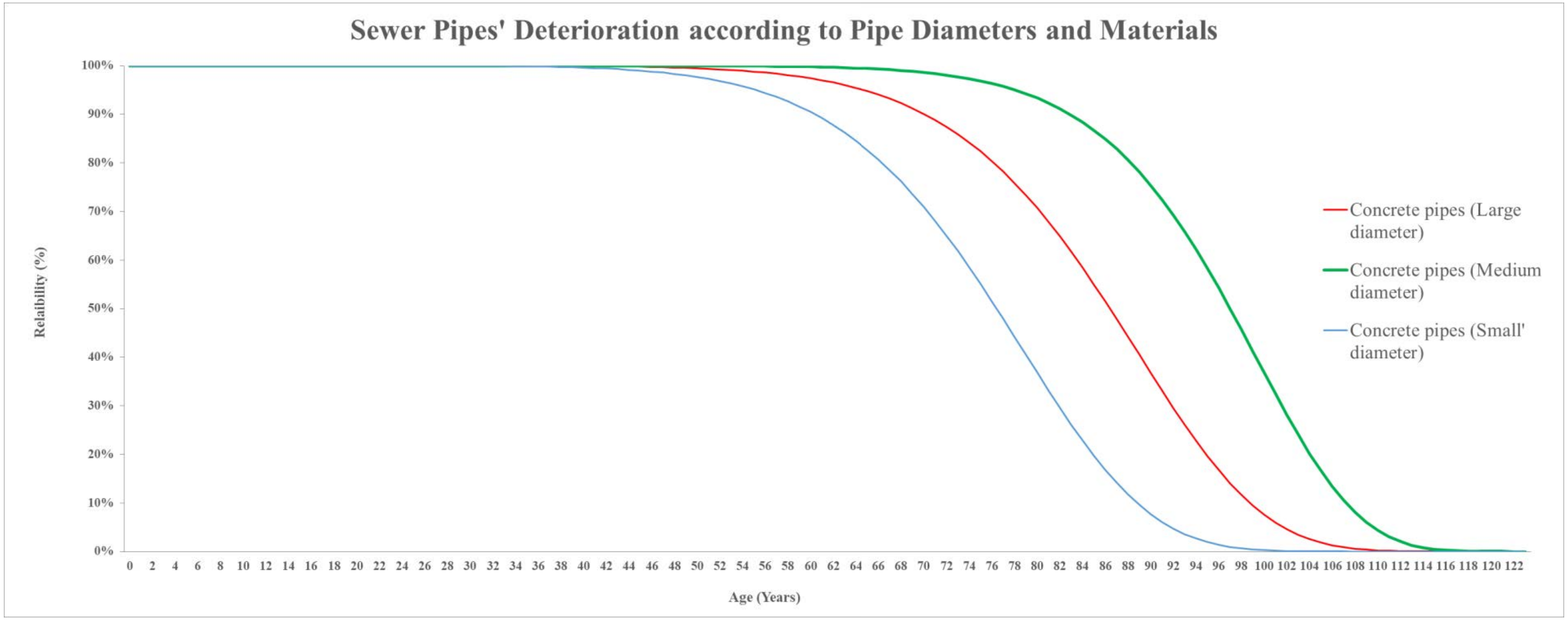


Figure 4.3: *Sewer pipes' deterioration according to different pipe diameters and materials*

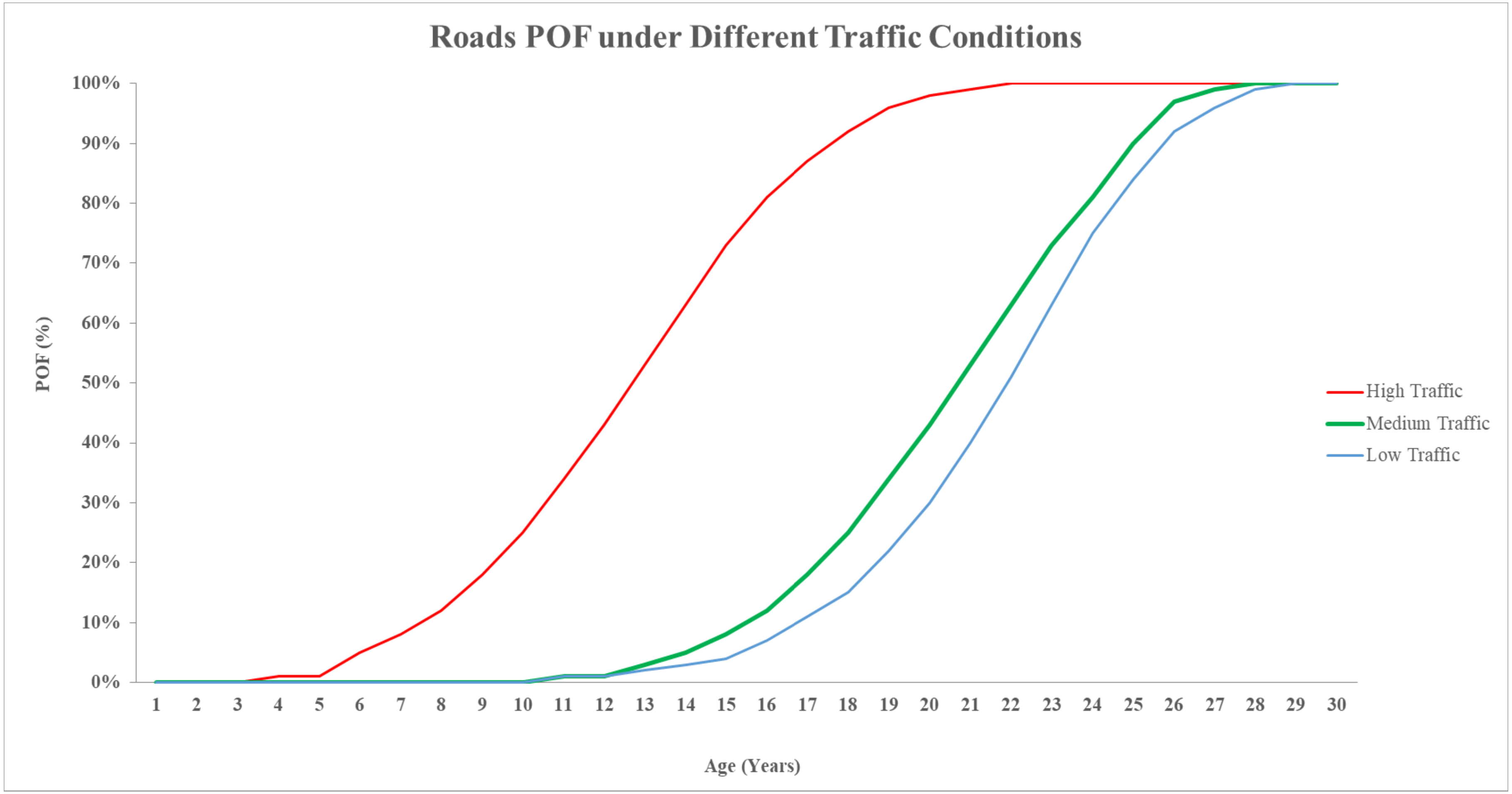


Figure 4.4: *Roads' POF under different traffic operational conditions*

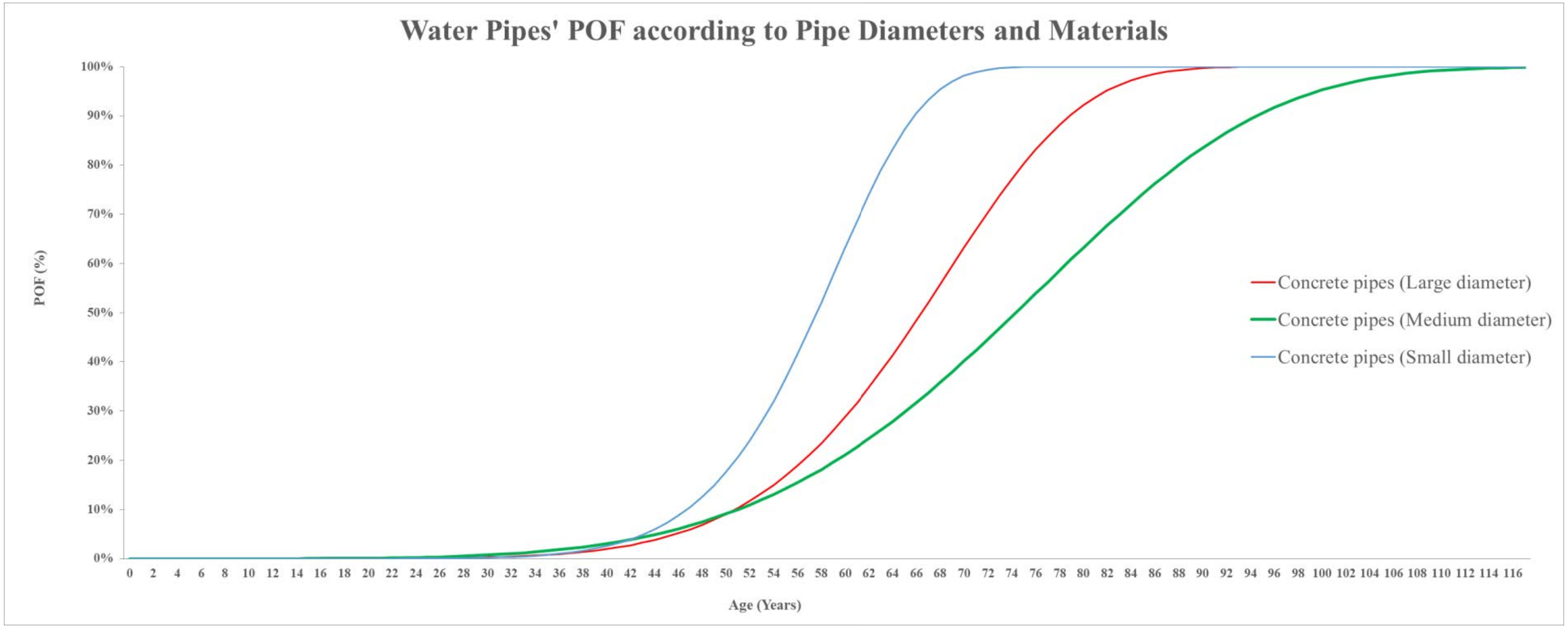


Figure 4.5: *Water pipes' POF according to different pipe diameters and materials*

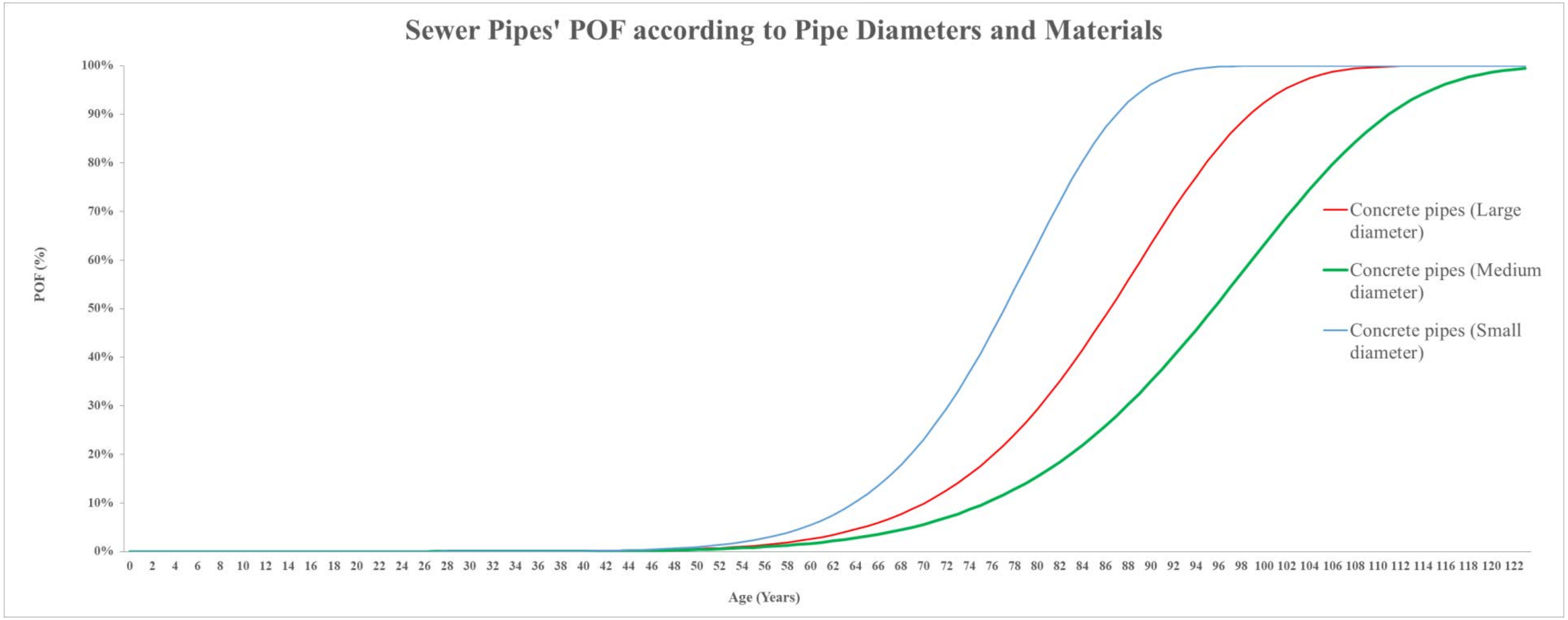


Figure 4.6: *Sewer pipes' POF according to different pipe diameters and materials*

Table 4-8: *Probability of failure ranges and reliability relations*

POF score range	POF description	System condition	Reliability values
0.9 - 1	Almost certain	Failing	Roads: $0 < R_r < 30$
			Water: $1 < R_w < 0.85$
			Sewer: $1 < R_s < 0.9$
0.7 - 0.9	Most Likely	Poor	Roads: $30 < R_r < 45$
			Water: $0.85 < R_w < 0.65$
			Sewer: $0.9 < R_s < 0.7$
0.5 - 0.7	Likely	Fair	Roads: $45 < R_r < 60$
			Water: $0.65 < R_w < 0.35$
			Sewer: $0.7 < R_s < 0.4$
0.25 - 0.5	Unlikely	Good	Roads: $60 < R_r < 80$
			Water: $0.35 < R_w < 0.15$
			Sewer: $0.4 < R_s < 0.2$
0.01 - 0.25	Rare	Excellent	Roads: $80 < R_r < 100$
			Water: $0.15 < R_w < 0.01$
			Sewer: $0.2 < R_s < 0.01$

Table 4-9: *Risk consequences scoring description*

Score	Consequence level	Description
1	Insignificant	No significant impact
		Little or no public exposure
		No impact on health risk
		Can be tolerated indefinitely
2	Minor	Limited public exposure
		Minor health risk
		Can be tolerated for an expected period of time
3	Moderate	Minor public exposure
		Health risk on a small part of the population
		Can be tolerated for a brief period of time (i.e. sufficient to plan and take action)
4	Major	Large part of the population at risk
		Requires expedient and/or emergency measures to address
5	Catastrophic	Major Impact for a large part of the population at risk
		Complete failure of systems
		Requires extreme emergency measures

4.2 Town of Kindersley Case Study

A 53 km stretch from the town of Kindersley roads, water, and combined sewer networks was selected for the analysis. The network comprises 125 corridors of spatially co-located roads, water, and sewer assets. In this case study, the dataset scale/size, in terms of the number of corridors, was scaled up 6 times, given the power of MOSEK linear and mixed-integer programming optimization algorithm. The case study was modeled and coded on REMOSOFT software as detailed in Appendix E. The dataset scale/size could be even expanded more as the model proved its ability to effectively solve the problem. The condition states of the corridors were adopted from the town of Kindersley case study (Amador and Magnuson 2011). Time value of money has been estimated at 2% interest rate (Trading Economics 2017; and Bank of Canada 2017). Furthermore, the study planning horizon was 25 years and could be expanded up to 100 years. The weights of the systems were assumed according to the overall LCC of each system across 100 years, using the longest life method. As highlighted earlier, the results displayed 45%, 25%, and 30% for the roads, water, and sewer systems respectively. However, those weights are subject to change according to the stakeholders' preferences (i.e. condition, replacement cost, crews' availability, etc.). The physical deterioration curves, financial information (i.e. intervention direct costs, indirect/user costs, etc.), temporal information (i.e. intervention time; disruption time, etc.), risk POF and COF scoring criteria are similar to the city of Montréal case study. The resilience preparedness dataset, which was excluded from the city of Montréal case study, will be thoroughly discussed in the upcoming sub-sections.

4.2.1 *Asset Inventory*

The asset inventory contains all the assets that are spatially located in the same corridor. In this case study, 125 corridors including roads, sewer, and water networks have been considered for the analysis as displayed in Appendix C – Sub-sections 8.3.1, 8.3.2, and 8.3.3 for roads, water, and sewer networks respectively. This information includes the corridor length, road width, number of lanes, area, average annual daily traffic, water or sewer pipe material and diameter, excavation depth, soil type, demand category, age/year or installation, etc. The asset inventory acts as a central database for the computational models such that all the necessary information about the corridor could be extracted directly from the inventory and used for further analysis.

4.2.2 *Temporal Dataset*

The temporal dataset is similar to the city of Montréal case study. The unit rates could be displayed in Table 4-2 and Table 4-3 (Hachey 2017). Thus, similar intervention disruption time was utilized for the two case studies. A summary of the combined average unit rates could be displayed in Table 4-10. A sample of the repair time curves that are extracted from REMSOFT could be displayed in Appendix C - Sub-section 8.3.5.

4.2.3 *Spatial Dataset*

The town of Kindersley is a triangular-shaped urban area as displayed in Figure **4.7**. For the combined sewer and stormwater network, there were two hydrologic models as shown in Figure **4.8**. The network comprises 125 pipes of different materials, diameters, length, etc. as outlined earlier in Table 8-24, Table 8-25 and Table 8-26 (Town of Kindersley 2011). Furthermore, the area savings for the partial and fully-coordinated intervention scenarios as opposed to the conventional intervention scenario were computed for each corridor depending on several factors as highlighted earlier. Table 4-4 summarizes the average % of area savings due to coordinating the intervention activities either partially or fully. However, the area savings differ from one corridor to another according to the excavation depth, pipe diameter, site conditions, etc. Further spatial analysis of the assets' distribution in the town of Kindersley could be displayed in Appendix C - Sub-section 8.3.4.

4.2.4 *Financial Dataset*

The financial dataset is similar to the city of Montréal case study. The costs could be displayed in Table 4-5, Table **4-6**, and Table **4-7** (Ville de Montréal 2017a; Ville de Montréal 2017b; Forterra 2017; Qin and Cutler 2014; and TDOT 2016). Thus, similar intervention direct and indirect costs were utilized for the two case studies. A summary of the combined average direct and indirect costs could be displayed in Table 4-11. A sample of the repair cost curves that are extracted from REMSOFT could be displayed in Appendix C - Sub-section 8.3.5.

4.2.5 *Physical Dataset*

The deterioration curves of both cases are similar. However, they differ in the number of corridors, current asset age, asset materials, pipe diameters', etc. For the roads, the deterioration curves could be displayed in Figure 4.1. For the water pipes, the deterioration curves could be displayed in Figure 4.2. For the combined sewer and stormwater pipes, the deterioration curves could be displayed in Figure 4.3. Thus, similar deterioration curves for the different asset categories were developed on the two modeling platforms. A sample of the deterioration curves that are extracted from REMSOFT could be displayed in Appendix C - Sub-section 8.3.5.

4.2.6 *Resilience Preparedness Dataset*

The resilience preparedness dataset includes all the information necessary to compute the resilience preparedness of the water and sewer assets within each corridor. This information includes the demand and capacity data for each pipe within both networks. The estimation of the current demand is based on the estimation of the water flow from the rational method. For the combined sewer and stormwater network, two networks with two different outfalls were analyzed, as displayed in Figure **4.8**, and accordingly, two hydrological models were built in StormCAD to estimate the current and future flow demand and capacity of each pipe in the network (Bentley 2018). The modeling starts by defining the catchment area and breaking it down into sub-catchments. Thenceforth, land use categories and topography information are used to identify and determine the drainage area for each land type and associated impervious area for each sub-basin. Discharge water moves to the related inlet through the sub-catchment. For each sub-catchment, the rational runoff coefficient is assigned based on the composite runoff index. Hence after, the concentration-time (i.e. the time needed for the stormwater to flow from the most remote point in the sub-catchment to the inlet) is defined for each sub-catchment and intensity duration frequency data are used to compute the future demand. In this study, one catch-basin/manhole component per sub-catchment was assumed as the main point to get discharged water into the pipes system. From each main inlet, water goes to a pipe and the flow-demand is estimated and analyzed. The catchment runoff, inlets, junctions, gutters, pipe networks, and outfalls computations were provided by StormCAD using the rational method to compute the peak flow of combined sewer and stormwater. Furthermore, sub-catchment areas were modeled to define the region's influence within the urban area that tributes to each series of catchments. The slope of the terrain was the main consideration for modeling the direction of the runoff. Current demand flow-capacity and future demand-capacity ratios were obtained from the hydrologic models by dividing the hydraulic demand flow over each pipe's capacity, calculated based on the pipe's physical attributes as highlighted earlier in the previous chapter. For the future demand, a 12% increase in rainfall intensity due to climate change was considered to update the runoff (Mailhot *et al.* 2012). The runoff coefficient could be estimated from the corresponding values of the return period from the IDF curves (Environment Canada 2014). For the water and combined sewer and stormwater pipes, the future demand was computed. Thus, population growth and future land uses were utilized to update the imperviousness coefficient (*C*). Spatial data from the Landsat of the United States Geological Survey (USGS) was used to analyze the imperviousness and vegetation changes from 1988 to 2013 in Kindersley, Saskatchewan. The total area of each land use class was computed with respect to the total study region area from 1988 to 2013 and the historical data trend was used to predict the future demand of each pipe. Runoff coefficients were selected based on each type of land cover (Water security agency 2014). For the demand-capacity prediction, land use/cover modeling was used to display the trend for each pipe from 1988 to 2013, as outlined in Table 4-12. In summary, water and combined sewer and stormwater pipes were classified into three groups as follows: (1) low demand pipes that are receiving very little changing demand across the future, (2) medium demand pipes that are receiving a moderate changing demand across the future; and (3) high demand pipes that are receiving a large amount of increasing flow demand across the future. The concept of pipe's apparent age was used to estimate the flow demand-capacity predication trend, as displayed in Figure **4.9**. For each pipe, the pipe's apparent age is estimated through matching its current flow demand-capacity ratio with the assigned demand trend (i.e. low, medium, high). Then, the future prediction of the demand is computed based on the developed prediction curves. A sample of the demand-capacity curves that are extracted from REMSOFT could be displayed in Appendix C - Sub-section 8.3.5.

4.2.7 *Risk Dataset*

The risk dataset is similar to the city of Montréal case study. For the POF, Table 4-8 was used to classify the POF for the roads, water, and combined sewer and stormwater networks. There are different POF curves to account for different asset categories as displayed in Figure 4.4, Figure 4.5, and Figure 4.6 for roads, water, and combined sewer and stormwater assets respectively. Regarding the COF, the scoring ranges between 1 and 5 from insignificant to catastrophic respectively, as displayed in Table 4-9. Thus, the same POF and COF scoring criteria were utilized for the two case studies.

Table 4-10: *Average unit rates (Town of Kindersley)*

Intervention name	Assets			Coordination	Average unit rate (hr/unit)	Unit	Notes
	Road	Water	Sewer				
Crack Sealing	■			Conventional	0.50	linear meter	Varies according to the number of lanes, road structural type, and traffic
Micro surfacing	■			Conventional	4.00	m^2	Varies according to the number of lanes, road structural type, and traffic
Patching	■			Conventional	9.00	m^2	Varies according to the number of lanes, road structural type, and traffic
Resurfacing	■			Conventional	15.00	m^2	Varies according to the number of lanes, road structural type, and traffic
Reconstruction	■			Conventional	25.00	m^2	Varies according to the number of lanes, road structural type, and traffic
Water pipelining		■		Conventional	1.50	linear meter	Varies according to the pipe material, pipe diameter, and excavation depth
Water pipe replacement		■		Conventional	2.00	linear meter	Varies according to the pipe material, pipe diameter, and excavation depth
Sewer pipelining			■	Conventional	2.50	linear meter	Varies according to the pipe material, pipe diameter, and excavation depth
Sewer pipe replacement			■	Conventional	3.00	linear meter	Varies according to the pipe material, pipe diameter, and excavation depth
Roads and water coordination	■	■		Partially-coordinated	3.50	linear meter	Varies according to the pipe material, pipe diameter, and excavation depth
Roads and sewer coordination	■		■	Partially-coordinated	4.50	linear meter	Varies according to the pipe material, pipe diameter, and excavation depth
Water and sewer coordination		■	■	Partially-coordinated	5.00	linear meter	Varies according to the pipe material, pipe diameter, and excavation depth
Full coordination (roads, water, and sewer)	■	■	■	Fully-coordinated	5.00	linear meter	Varies according to the pipe material, pipe diameter, and excavation depth

Figure 4.7: *GIS maps for the town of Kindersley's roads, water, and sewer network*

Table 4-11: *Average unit cost including direct and indirect costs (Town of Kindersley)*

Intervention name	Assets			Coordination	Average unit cost ($/unit)	Unit	Notes
	Road	Water	Sewer				
Crack Sealing				Conventional	$ 0.75	linear meter	Varies according to the number of lanes, road structural type, and traffic
Micro surfacing				Conventional	$ 8.00	m^2	Varies according to the number of lanes, road structural type, and traffic
Patching				Conventional	$ 60.00	m^2	Varies according to the number of lanes, road structural type, and traffic
Resurfacing				Conventional	$ 90.00	m^2	Varies according to the number of lanes, road structural type, and traffic
Reconstruction				Conventional	$ 145.00	m^2	Varies according to the number of lanes, road structural type, and traffic
Water pipelining				Conventional	$ 1,200.00	linear meter	Varies according to the pipe material, pipe diameter, and excavation depth
Water pipe replacement				Conventional	$ 1,750.00	linear meter	Varies according to the pipe material, pipe diameter, and excavation depth
Sewer pipelining				Conventional	$ 1,450.00	linear meter	Varies according to the pipe material, pipe diameter, and excavation depth
Sewer pipe replacement				Conventional	$ 2,200.00	linear meter	Varies according to the pipe material, pipe diameter, and excavation depth
Roads and water coordination				Partially-coordinated	$ 1,800.00	linear meter	Varies according to the pipe material, pipe diameter, and excavation depth
Roads and sewer coordination				Partially-coordinated	$ 2,250.00	linear meter	Varies according to the pipe material, pipe diameter, and excavation depth
Water and sewer coordination				Partially-coordinated	$ 2,800.00	linear meter	Varies according to the pipe material, pipe diameter, and excavation depth
Full coordination (roads, water, and sewer)				Fully-coordinated	$ 2,900.00	linear meter	Varies according to the pipe material, pipe diameter, and excavation depth

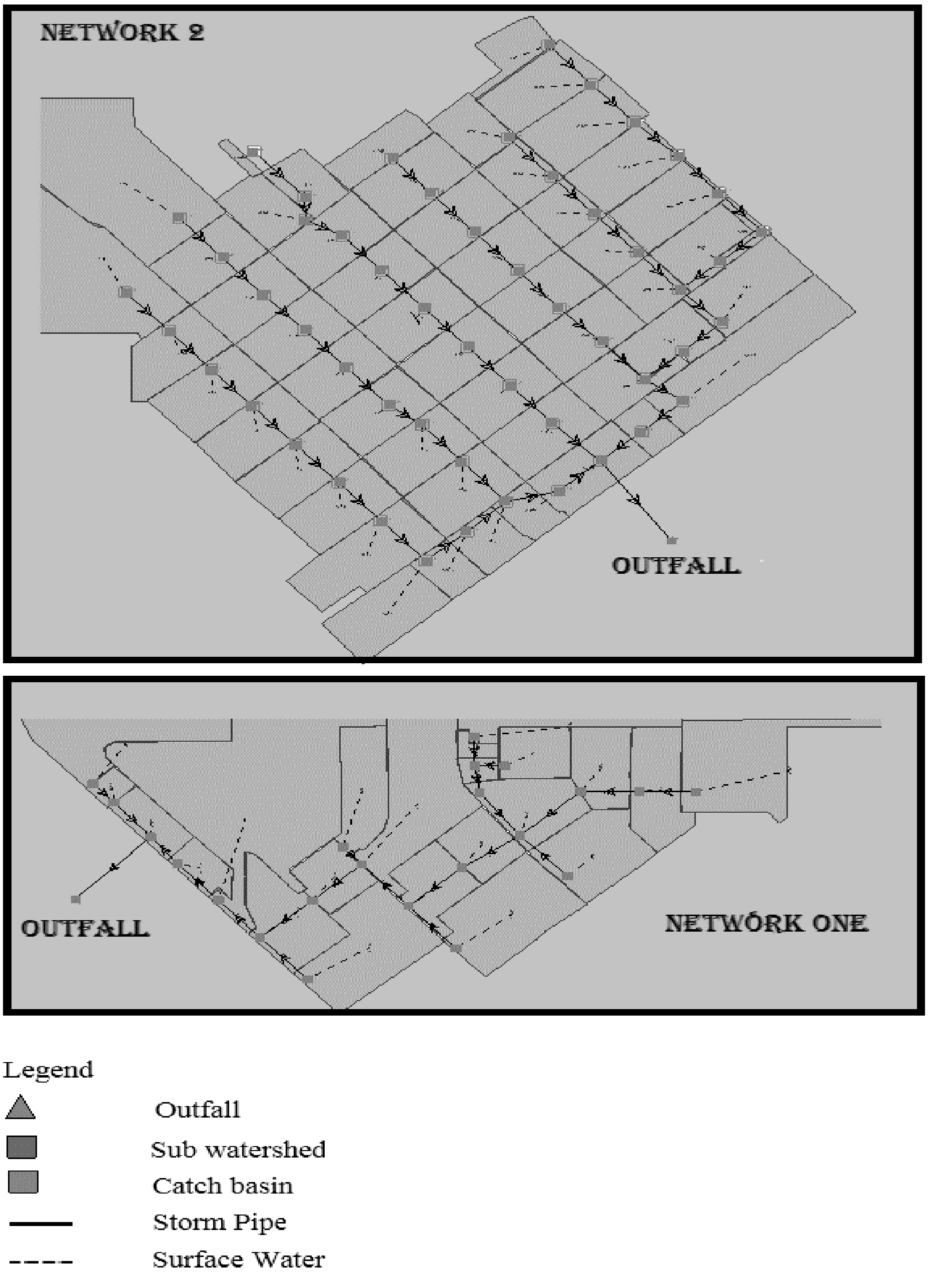


Figure 4.8: *StormCAD model for the town of Kindersley stormwater network*

Table 4-12: *Pipe land use/cover (%) statistics (Town of Kindersley)*

Year	Impervious	Green	Bare soil	Water
1988	17	60.5	20	2.5
1993	19	60.3	18	2.7
1998	27	53.4	17	2.6
2003	29	46.7	22	2.3
2008	38	42.4	17	2.6
2013	40	29.6	28	2.4

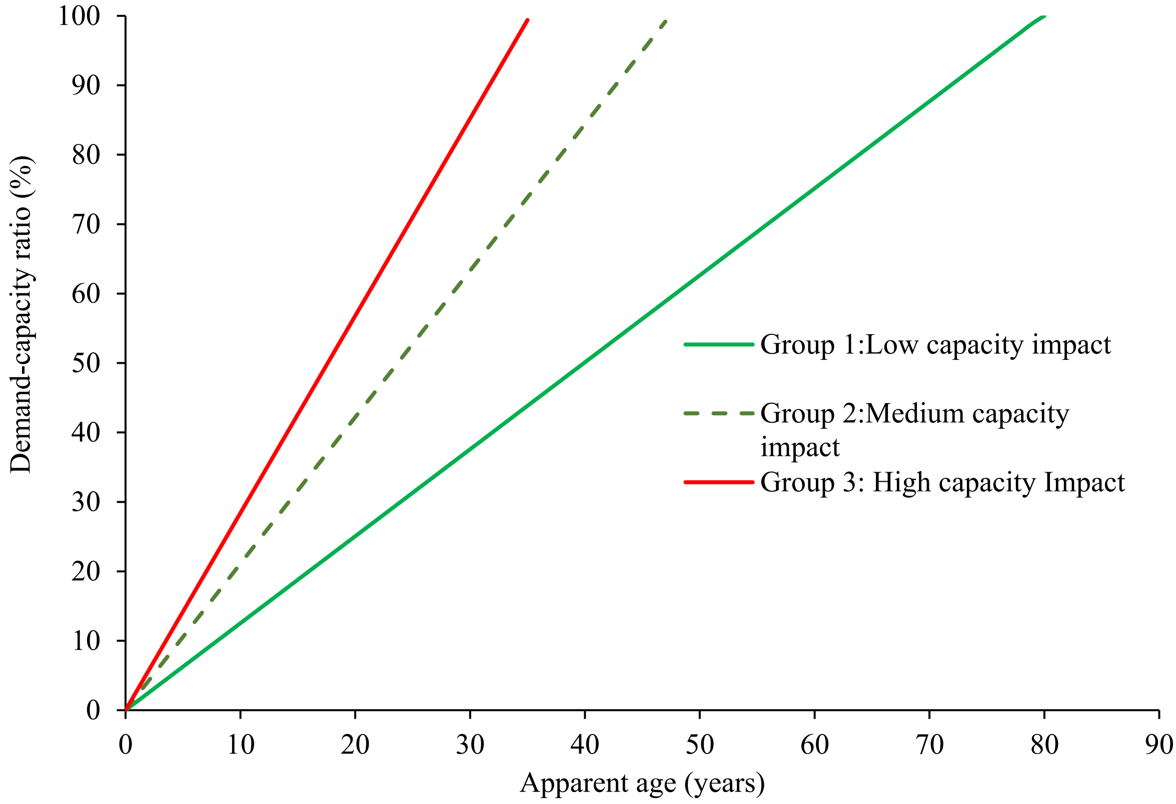


Figure 4.9: *Demand-capacity ratio of different pipe groups (Town of Kindersley)*

5 CHAPTER 5 – RESULTS AND ANALYSIS

This chapter aims at discussing the implementation of the developed models on the two case studies namely; city of Montréal and town of Kindersley. It starts with displaying the coordination savings in financial, temporal, and physical terms given the fact that those multi-dimensional performance assessment models are standalone, and they could be run without a full intervention plan. The static results are carried out on a random corridor, step-by-step calculations are illustrated, and the results are discussed and analyzed. Thenceforth, the system was applied to a 9 km stretch from the city of Montreal. It aims at displaying the pre-contract and post-contract optimization results and compares the results with the average results of the city's annual expenditures. It is worth mentioning that the city of Montréal case study excluded the resilience preparedness indicator due to the lack of available data for undertaking the analysis. Hence after, the town of Kindersley case study aims at expanding the capabilities of the system to solve large-scale combinatorial-in-nature problems with 125 corridors (53 km) across 25 years planning horizon, which can be further expanded either horizontally (i.e. extending the study planning horizon) or vertically (i.e. increasing the number of corridors and/or assets). The town of Kindersley results will be displayed for the post-contract optimization model. Furthermore, the results will be validated by comparing the model results with the town's annual expenditures as well as the conventional intervention schedule.

5.1 Static Results of Multi-Dimensional Performance Assessment Models

The multi-dimensional performance assessment model static results will be discussed and analyzed for the temporal, financial, and condition indicators only given the fact that the reliability, risk (POF), spatial, efficiency, and effectiveness are dynamic and rely on the existence of a full intervention plan to be computed. Thus, the full-scale implementation of the multi-dimensional performance assessment indicators will be further discussed after running the optimization in the two case studies as will be highlighted later.

5.1.1 *Duration savings*

The duration savings model aims at computing the temporal savings resulting from coordinating the interventions of the co-located systems. The results of this model represent a static standalone outcome of the time savings such that corridor 8 was randomly selected to visualize the potential temporal savings of the three intervention scenarios. However, the results might vary according to several aspects such as; corridor length, system's condition, intervention type, pipe material, and pipe diameter, etc. The dynamic results will be shown after running the optimization scenarios to display the network indicators and the overall savings across the planning horizon. The detailed computations of the corridor intervention duration for the different intervention types (i.e. minor or major rehabilitation) and scenarios (i.e. conventional, partially-coordinated, and fully-coordinated) were carried out and the outcome is a list of intervention scenarios with their associated durations as well as the maximum temporal coordination savings that can be attained as opposed to the conventional intervention scenario. Those results could be displayed in Table **5-1** and Table **5-2**. As shown in Table **5-1**, the duration to complete an entire intervention for the corridor in the three intervention coordination cases was computed. The results displayed substantial temporal savings with a corridor coordination ratio ranging between 16% and 38% for the partially-coordinated and fully-coordinated intervention scenarios as opposed to the conventional one. The temporal savings reflect the coordination of the intervention activities where the common activities have been carried out once instead of n_a or n_s times for the partially-coordinated and conventional intervention scenarios. Furthermore, undertaking the fully-coordinated intervention increased the number of parallel activities, which increased the temporal savings as opposed to the conventional approach by which n_s interventions are separately undertaken for each system.

5.1.2 *Financial savings*

The financial savings model aims at computing the financial savings resulting from coordinating the interventions of the co-located systems. Unlike the temporal model, the financial savings model functions through two modules as highlighted earlier, direct costs calculation module, and indirect costs calculation module. The output of the duration savings model is inputted to the indirect costs calculation module to precisely estimate the service disruption duration and compute the indirect costs accordingly. The results of this model represent a static standalone outcome of the cost savings such that corridor 8 was randomly selected to visualize the potential financial savings of the three intervention scenarios. However, the results vary according to several aspects such as; corridor length, system's condition, intervention type, pipe material, and pipe diameter, etc. The dynamic results will be shown after running the optimization scenarios to display the network indicators and the overall savings across the planning horizon. The detailed computations of the corridor intervention direct and indirect costs for the different intervention types (i.e. minor or major rehabilitation) and scenarios (i.e. conventional, partially-coordinated, and fully-coordinated) were carried out and the outcome is a list of intervention scenarios with their associated direct and indirect as well as the maximum financial coordination savings that can be attained as opposed to the conventional intervention scenario. The direct costs savings results could be displayed in Table **5-3**. The indirect costs savings results could be displayed in Table **5-4**. The LCC savings, represented through the LIF, could be displayed in Table **5-5**, Table **5-6**, and Table **5-7**. As shown in Table **5-5** and Table **5-6**, the direct and indirect intervention costs for maintaining all the systems in the corridor are summed up for the three intervention coordination scenarios. The results displayed substantial financial savings in the direct and indirect costs ranging between 16% and 41% for the partially-coordinated and fully-coordinated intervention scenarios as opposed to the conventional one. Accordingly, the results displayed huge financial savings with a LIF ranging between 19% and 39% for the partially-coordinated and fully-coordinated intervention scenarios as opposed to the conventional one. The financial savings reflect the coordination of the intervention activities where the common activities have been carried out once instead of n_a or n_s times for the partially-coordinated and conventional intervention scenarios. Furthermore, the fact that the fully-coordinated intervention results in less number of service disruptions as well as less disruption duration, as highlighted previously in the duration savings model, reduces the indirect costs and accordingly increases the financial savings.

5.1.3 *Integrated deterioration results*

The integrated deterioration model computes the condition/reliability of each system and combines them into an overall corridor condition, as highlighted earlier in the research methodology chapter. The roads network featured a regression deterioration while the water and sewer networks featured a Weibull deterioration. To display the corridor condition computation, a randomly selected sample of the reliability curves for the roads, water, and sewer networks was selected as displayed in Figure 5.1, Figure 5.2, and Figure 5.3. The expected service lives of the systems vary according to several factors (i.e. pipe material, pipe diameter, road structural category, etc.). The average service lives of the roads, water, and sewer networks were estimated at 15-30, 60-80, and 80-100 years respectively. As shown in Figure 5.1, Figure 5.2, and Figure 5.3, there are two reliability curves to represent each corridor where the first reliability curve displays the impact of the typical aging-based deterioration and the second reliability curve displays the impact of undertaking an intervention at any point of time. The corridor reliability is computed based on the weights of importance among the systems, as displayed in Figure 5.4. To dynamically visualize the interventions' reliability improvement, two intervention programs need to be compared together. Thus, the dynamic reliability improvement results will be further discussed in the two case studies.

Table 5-1: *Temporal results for the intervention scenario*

Corridor ID#	Asset Cost (Roads)		Asset Cost (Water)		Asset Cost (Sewer)		Roads and water	Roads and sewer	Water and sewer	Fully-coordinated
	Cracks Case	Resurfacing Case	Leaks Case	Replacement Case	Leaks Case	Replacement Case				
Corridor 8	59.25	137.61	60.46	69.56	59.88	69.76	69.56	69.76	84.66	94.66

Table 5-2: *Corridor coordination ratio for the intervention scenarios*

Corridor ID#	Corridor Coordination Ratio			
	Case 1 - Roads and Water	Case 2 - Roads and Sewer	Case 3 - Water and Sewer	Case 4 - Fully-coordinated
Corridor 8	31%	29%	16%	38%

Table 5-3: *Direct costs savings for the intervention scenarios*

Corridor ID#	LCC Improvement Factor - Direct Costs			
	Case 1 - Roads and Water	Case 2 - Roads and Sewer	Case 3 - Water and Sewer	Case 4 - Fully-coordinated
Corridor 8	17.81%	19.81%	22.02%	37.83%

Table 5-4: *Indirect costs savings for the intervention scenarios*

Corridor ID#	LCC Improvement Factor - Indirect Costs			
	Case 1 - Roads and Water	Case 2 - Roads and Sewer	Case 3 - Water and Sewer	Case 4 – Fully-coordinated
Corridor 8	36.69%	32.69%	16.13%	41.82%

Table 5-5: *LCC for the conventional intervention scenario*

Corridor ID#	LCC – Direct and Indirect Costs					
	Asset Cost (Roads)		Asset Cost (Water)		Asset Cost (Sewer)	
	Cracks Case	Resurfacing Case	Leaks Case	Replacement Case	Leaks Case	Replacement Case
Corridor 8	$47,968.80	$357,735.59	$46,802.29	$838,568.61	$50,802.29	$812,168.81

Table 5-6: *LCC for the partially-coordinated and fully-coordinated intervention scenarios*

Corridor ID#	LCC - Direct and Indirect Costs									
	Corridor Cost (Case 1 - Roads and Water)			Corridor Cost (Case 1 - Roads and Sewer)			Corridor Cost (Case 3 - Water and Sewer)			Corridor Cost (Case 4 - Fully-coordinated)
	Roads and Water Case	Sewer Case	Overall (Case 1)	Roads and Sewer Case	Water Case	Overall (Case 2)	Water and Sewer Case	Roads Case	Overall (Case 3)	Roads, Water and Sewer
Corridor 8	$838,568.61	$812,168.81	$1,650,737.42	$812,168.81	$838,568.61	$1,650,737.42	$1,248,703.05	$357,735.59	$1,606,438.64	$1,248,703.05

Table 5-7: *LCC savings for the intervention scenarios*

Corridor ID#	LCC Improvement Factor – Direct and Indirect Costs			
	Case 1 - Roads and Water	Case 2 - Roads and Sewer	Case 3 - Water and Sewer	Case 4 – Fully-coordinated
Corridor 8	19.62%	21.35%	20.52%	39.49%

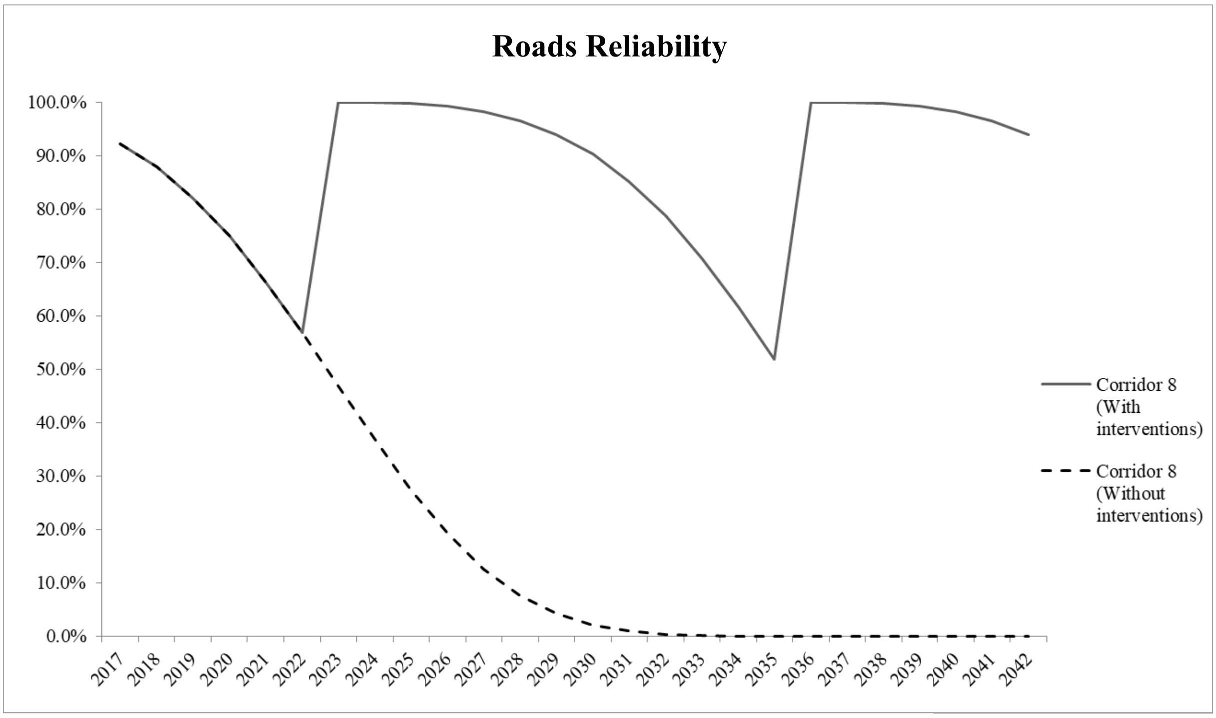


Figure 5.1: *Sample from the roads' reliability model*

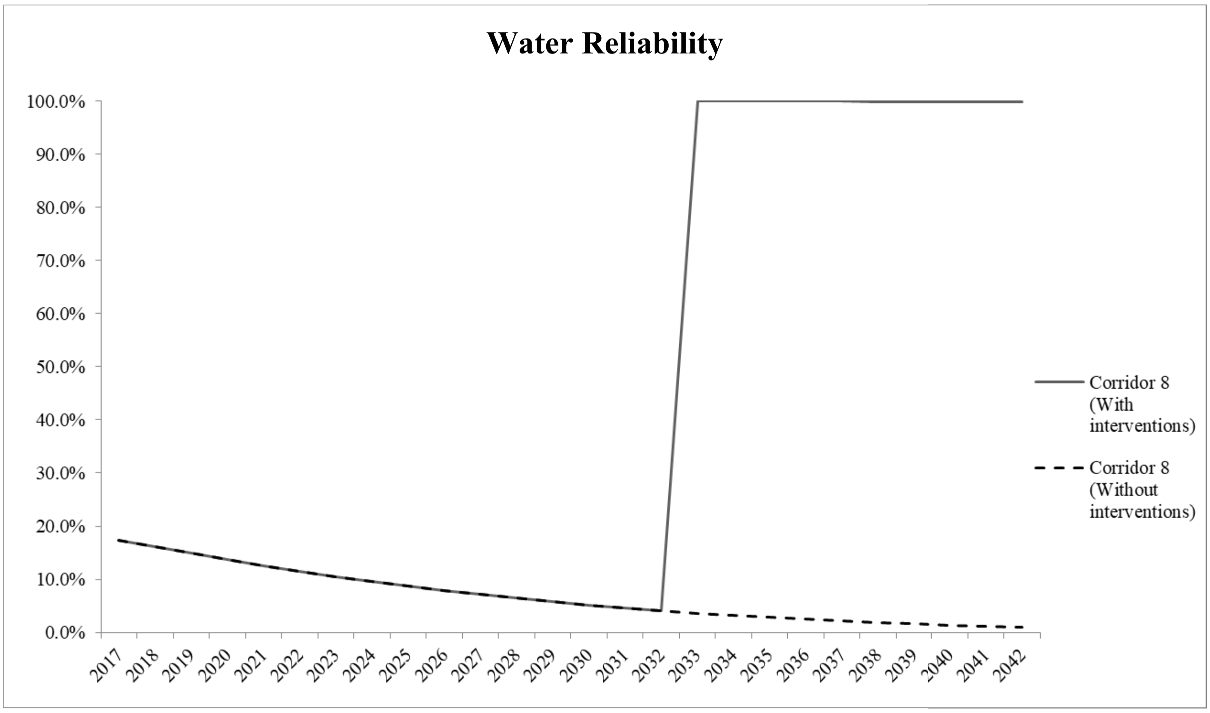


Figure 5.2: *Sample from the water reliability model*

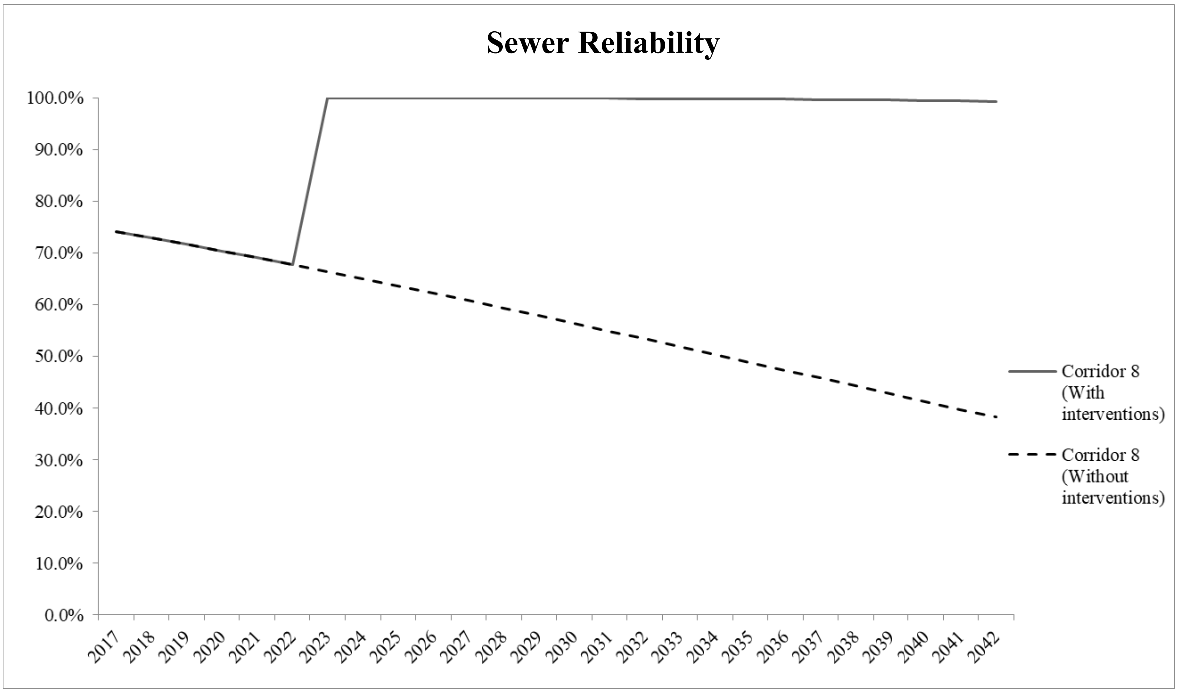


Figure 5.3: *Sample from the sewer reliability model*

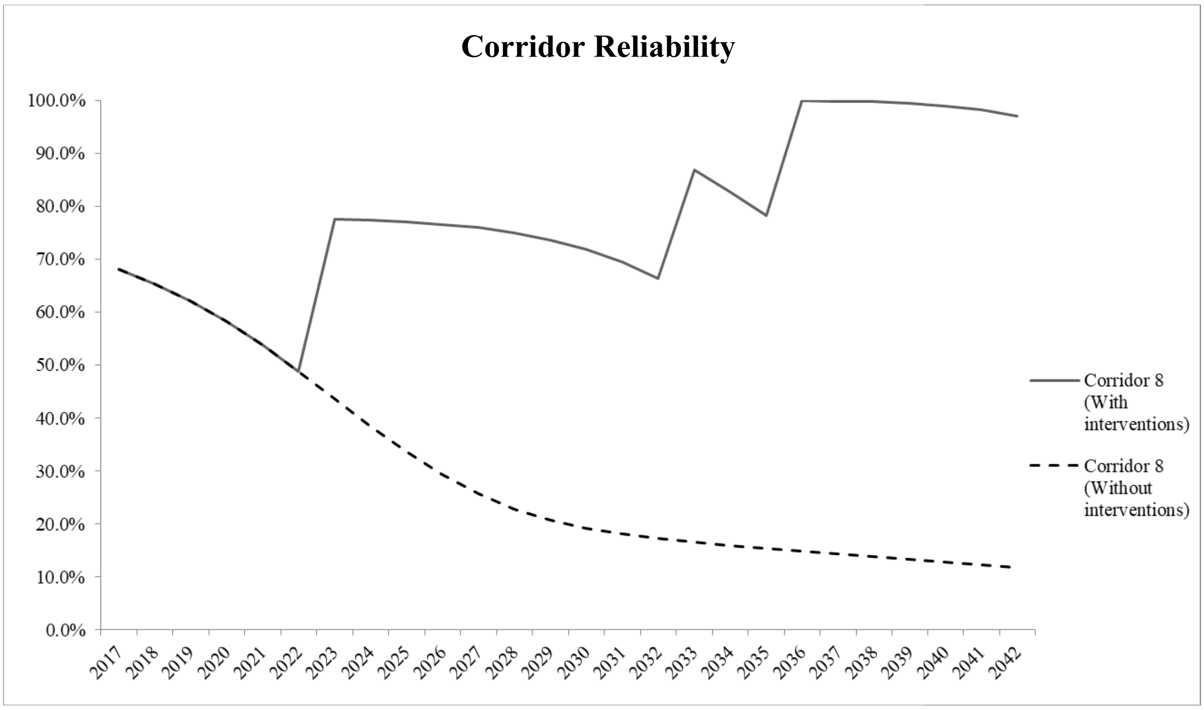


Figure 5.4: *Sample from the integrated corridor reliability model*

5.2 City of Montréal Case Study

A 9 km stretch from the city of Montréal was selected for applying the system. The optimization model was run on both the pre-contract and post-contract optimization modes across 25 years planning horizon using GAs optimization engine. For the pre-contract optimization, the results were the KPIs' thresholds as well as the financial penalties and incentives for each KPI. However, the post-contract optimization results aim at reaching a near-optimal intervention plan for several scenarios as follows: (1) conventional optimization that reaches a near-optimal solution for each asset under study; (2) coordination optimization that accounts for conventional, partial, and full coordination scenarios while reaching a near-optimal intervention plan. The results' discussion will be divided into three sub-sections: (1) optimization results; (2) sensitivity analysis; and (3) model validation. The optimization results will discuss the pre-contract and post-contract optimization results. Hence after, the sensitivity analysis aims at analyzing the impact of changing the reliability KPI threshold on the other KPIs; and comparing it with the baseline scenario. Finally, the optimization model results will be compared and validated with the average annual city's expenditures.

5.2.1 *Optimization Results*

5.2.1.1 *Pre-Contract Optimization*

The pre-contract optimization model was run in two modes: (1) KPIs' thresholds; and (2) P/I values. The 1st mode, KPIs' thresholds, aims at obtaining the optimum KPIs' threshold limits that ensure the delivery of safe, sustainable, and financially-feasible services to the public with minimal risks of failure and tolerable temporal and spatial public disruption. The optimization model was applied to the city of Montréal dataset with minimum and maximum values for the thresholds as well as annual budget and unacceptable physical reliability set as constraints while running the model. The study planning horizon was 25 years. As discussed earlier, the optimization model featured a GA-based optimization engine with the attributes outlined in Table **5-8**. The results are displayed in Table **5-9**. The results were divided into single asset-based thresholds and corridor-based thresholds given the fact that the model accounts for both conventional and fully-coordinated coordination scenarios. The optimization model was run three times to reach the single KPIs' thresholds and one time to reach the corridor-based KPIs' thresholds. It is worth noting that both the safety performance measures along with their penalties and incentives and the roads' operational KPIs along with their associated thresholds were adopted from a previous study and were not included in the analysis of this study (Abu- Samra 2015). The roads' operational KPIs along with their associated thresholds could be displayed in Table **5-10**. Detailed description of each performance measure and KPI were outlined in Table **5-9**. The 2nd mode, P/I values, aims at obtaining the optimum set of financial penalties and incentives, corresponding to the KPIs' threshold defined earlier in the 1st mode. The model was applied to the city of Montréal dataset with minimum and maximum values for the thresholds as well as annual budget and unacceptable physical reliability set as constraints while running the model. Furthermore, the penalties' and incentives' applicability criteria were mathematically defined to be included in the financial computations, as highlighted earlier in Equations 3.89 and 3.90 for penalties and incentives application respectively. Similar to the previous optimization mode, the optimization model featured a GA-based optimization engine with similar attributes defined in Table **5-8**. The results are displayed in Table **5-11**. The results were divided into single asset-based thresholds and corridor-based thresholds given the fact that the model accounts for both conventional and fully-coordinated coordination scenarios. The optimization model was run three times to reach the single KPIs' thresholds and one time to reach the corridor-based KPIs' thresholds. It is worth noting that penalties and incentives are applied to an asset-basis or corridor-basis, depending on which threshold was not met. In case both thresholds were not met, the corridor-based penalties or incentives value precedes and is accordingly applied to the financial model. Furthermore, in case the KPIs' thresholds are not met or ar met for a certain corridor at a certain point of time, the highest penalty or incentive value is applied. The model did not consider other forms of penalties or incentives such as; reduction or expansion of the contractual period, etc.

Table 5-8: *Pre-contract optimization results – KPI thresholds*

Optimization Parameters	Value
Engine	GA (Evolver 7.5)
Crossover	80%
Mutation	20%
Population	200
Stopping criteria	Progress-based – No improvement in the objective function for 100,000 trials

Table 5-9: *Pre-contract optimization results – KPI thresholds*

Performance measure	KPI	Description	KPIs' Thresholds (per corridor)				Unit (per corridor)
			Roads	Water	Sewer	Corridor	
Financial	LIF	Available budget	Varies*	Varies*	Varies*	Varies*	N/A
Temporal	NCR	Amount of time allotted for disruption every 5 years	5	30	30	35	business days every 5 years
		Maximum amount of time allotted for a single disruption	3	30	30	35	business days per intervention
Spatial	STIF	Spatial extent of a single disruption	500	500	500	500	linear meter per intervention
		Maximum number of disruptions every 5 years	1	1	1	1	number of disruptions per year
		Maximum number of revisits every 5 years (excluding road preventive maintenance i.e. crack sealing, potholes repair, etc.)	2	1	1	2	number of visits every 5 years
Physical	CIF	Minimum acceptable reliability at any point of time (Detailed KPIs for the roads are discussed in Table **5-10**)	65%	50%	50%	60%	%
Risk	RIF	Maximum acceptable risk threshold at any point of time	35%	50%	50%	40%	%
Resilience Preparedness	RPIF	Maximum demand/capacity ratio at any point of time to avoid combined sewer and stormwater overflooding or unmet water demand	N/A	80%	75%	75%	%
Efficiency	IEF	Maximum number of disruptions to undertake interventions for all the corridor assets	N/A	N/A	N/A	3	number of interventions
		Maximum number of years to undertake interventions for all the corridor assets	N/A	N/A	N/A	12	years
		Minimum spacing between interventions within the same corridor	N/A	N/A	N/A	4	years
Effectiveness	IFF	Minimum amount of operating time (i.e. free of intervention) excluding the preventive maintenance actions (i.e. crack sealing, potholes repairs, etc.)	N/A	N/A	N/A	8	years
Safety	N/A	Maximum number of accidents per year due to poor asset condition (i.e. severity level is accounted for in the accidents' police report - fatalities are treated separately)	N/A	N/A	N/A	12	number of accidents per year
		Maximum number of accidents per year due to poor maintenance management (i.e. signs, flagman, etc.)	N/A	N/A	N/A	2	number of accidents per year
		Maximum response time for accidents' removal	N/A	N/A	N/A	4	hours
		Maximum response time for repairing potholes	N/A	N/A	N/A	5	business days
		Maximum response time for barriers' removal	N/A	N/A	N/A	2	business days
		Maximum response time for repairing defective guardrails	N/A	N/A	N/A	2	business days

Table 5-10: *Road operational KPIs and their associated thresholds*

Performance measure	KPI	Description	KPIs' Thresholds (Roads)	Unit
Physical	Surface rating	Minimum acceptable surface rating for the corridor (i.e. surface distresses-based deductions are used to obtain the surface rating)	8.00	Scale from 0-10 (0: failing road surface; 10: excellent/pristine road surface)
	Rutting	Maximum acceptable rutting depth	9.00	millimeters (mm)
	Alligator cracking	Maximum acceptable extent (%) of the alligator cracking within the corridor	30%	%
	International roughness index	Minimum acceptable roughness index for the corridor (i.e. measures the characteristic of the longitudinal profile of a traveled wheel track)	2.60	meter per kilometer (m/km) - scale from 0 to 5 (0: unacceptable; 5: excellent)

Table 5-11: *Pre-contract optimization results – Penalties and Incentives*

Performance measure	KPI	Description	Penalties ($)				Incentives ($)				Penalties Application Criteria	Penalty Application Frequency	Incentives Application Criteria	Incentive Application Frequency
			Roads	Water	Sewer	Corridor	Roads	Water	Sewer	Corridor				
Financial	LIF	Available budget	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	Applied whenever the maintenance contractor fails to comply with the pre-defined contractual threshold	Penalty value per year (lump sum)	Applied after meeting the pre-defined contractual threshold for 4 consecutive years	Incentive value per 4 years (lump sum)
Temporal	NCR	Amount of time allotted for disruption every 5 years	$50.00	$20.00	$30.00	$100.00	$500.00	$1,000.00	$1,500.00	$3,000.00	Applied whenever the maintenance contractor fails to comply with the pre-defined contractual threshold	Penalty value per day per time	Applied after meeting the pre-defined contractual threshold for 2 consecutive times (10 years)	Incentive value per 10 years (lump sum)
		Maximum amount of time allotted for a single disruption	$40.00	$60.00	$100.00	$200.00	$200.00	$300.00	$500.00	$1,000.00	Applied whenever the maintenance contractor fails to comply with the pre-defined contractual threshold	Penalty value per day per time	Applied after meeting the pre-defined contractual threshold for 2 consecutive times	Incentive value per time (lump sum)
Spatial	STIF	Spatial extent of a single disruption	$1.50	$3.50	$4.00	$9.00	$100.00	$150.00	$250.00	$500.00	Applied whenever the maintenance contractor fails to comply with the pre-defined contractual threshold	Penalty value per extra meter per intervention	Applied after meeting the pre-defined contractual threshold for 3 consecutive times	Incentive value per time (lump sum)
		Maximum number of disruptions every 5 years	$40.00	$60.00	$100.00	$200.00	$200.00	$300.00	$500.00	$1,000.00	Applied whenever the maintenance contractor fails to comply with the pre-defined contractual threshold	Penalty value per extra day per intervention	Applied after meeting the pre-defined contractual threshold for 3 consecutive times	Incentive value per time (lump sum)
		Maximum number of revisits every 5 years (excluding road preventive maintenance i.e. crack sealing, potholes repair, etc.)	$40.00	$60.00	$100.00	$200.00	$200.00	$300.00	$500.00	$1,000.00	Applied whenever the maintenance contractor fails to comply with the pre-defined contractual threshold	Penalty value per extra day per intervention	Applied after meeting the pre-defined contractual threshold for 3 consecutive times	Incentive value per time (lump sum)
Physical	CIF	Minimum acceptable reliability at any point of time	$4,000.00	$3,000.0	$3,000.00	$10,000.00	$5,000.00	$2,500.00	$2,500.00	$10,000.00	Applied whenever the maintenance contractor fails to comply with the pre-defined contractual threshold	Penalty value per year (lump sum)	Applied after meeting the pre-defined contractual threshold for 4 consecutive years	Incentive value per time (lump sum)
Risk	RIF	Maximum acceptable risk threshold at any point of time	$4,000.00	$3,000.0	$3,000.00	$10,000.00	$5,000.00	$2,500.00	$2,500.00	$10,000.00	Applied whenever the maintenance contractor fails to comply with the pre-defined contractual threshold	Penalty value per year (lump sum)	Applied after meeting the pre-defined contractual threshold for 4 consecutive years	Incentive value per time (lump sum)
Resilience Preparedness	RPIF	Maximum demand/capacity ratio at any point of time to avoid combined sewer and stormwater overflooding or unmet water demand	$4,000.00	$3,000.0	$3,000.00	$10,000.00	$5,000.00	$2,500.00	$2,500.00	$10,000.00	Applied whenever the maintenance contractor fails to comply with the pre-defined contractual threshold	Penalty value per year (lump sum)	Applied after meeting the pre-defined contractual threshold for 4 consecutive years	Incentive value per time (lump sum)
Efficiency	IEF	Maximum number of disruptions to undertake interventions for all the corridor assets	N/A	N/A	N/A	$200.00	N/A	N/A	N/A	$500.00	Applied whenever the maintenance contractor fails to comply with the pre-defined contractual threshold	Penalty value per additional intervention	Applied after meeting the pre-defined contractual threshold	Incentive value per time per reduced intervention (lump sum)
		Maximum number of years to undertake interventions for all the corridor assets	N/A	N/A	N/A	$2,000.00	N/A	N/A	N/A	$600.00	Applied whenever the maintenance contractor fails to comply with the pre-defined contractual threshold	Penalty value per year per time	Applied after meeting the pre-defined contractual threshold	Incentive value per time (lump sum)

Performance measure	KPI	Description	Penalties ($)				Incentives ($)				Penalties Application Criteria	Penalty Application Frequency	Incentives Application Criteria	Incentive Application Frequency
			Roads	Water	Sewer	Corridor	Roads	Water	Sewer	Corridor				
		Minimum spacing between interventions within the same corridor	N/A	N/A	N/A	$1,000.00	N/A	N/A	N/A	$800.00	Applied whenever the maintenance contractor fails to comply with the pre-defined contractual threshold	Penalty value per year per time	Applied after meeting the pre-defined contractual threshold	Incentive value per time (lump sum)
Effectiveness	IFF	Minimum amount of operating time (i.e. free of intervention) excluding the preventive maintenance actions (i.e. crack sealing, potholes repairs, etc.)	N/A	N/A	N/A	$3,000.00	N/A	N/A	N/A	$1,000.00	Applied whenever the maintenance contractor fails to comply with the pre-defined contractual threshold	Penalty value per year per time	Applied after meeting the pre-defined contractual threshold	Incentive value per time (lump sum)
Safety	N/A	Maximum number of accidents per year due to poor asset condition (i.e. severity level is accounted for in the accidents' police report - fatalities are treated separately)	N/A	N/A	N/A	$4,000.00	N/A	N/A	N/A	$500.00	Applied whenever the maintenance contractor fails to comply with the pre-defined contractual threshold	Penalty value per extra accident	Applied whenever the actual number of accidents per year becomes less than the pre-defined contractual threshold for 2 consecutive years	Incentive value per reduced accident
		Maximum number of accidents per year due to poor maintenance management (i.e. signs, flagman, etc.)	N/A	N/A	N/A	$8,000.00	N/A	N/A	N/A	$300.00	Applied whenever the maintenance contractor fails to comply with the pre-defined contractual threshold	Penalty value per extra accident	Applied whenever the actual number of accidents per year becomes less than the pre-defined contractual threshold for 2 consecutive years	Incentive value per reduced accident
		Maximum response time for accidents' removal	N/A	N/A	N/A	$300.00	N/A	N/A	N/A	$150.00	Applied whenever the maintenance contractor fails to respond within the pre-defined response time	Penalty value per additional hour per accident	Applied whenever the maintenance contractor responds within the pre-defined response time for 3 consecutive times	Incentive value per reduced hour per accident
		Maximum response time for repairing potholes	N/A	N/A	N/A	$200.00	N/A	N/A	N/A	$100.00	Applied whenever the maintenance contractor fails to respond within the pre-defined response time	Penalty value per additional day per pothole	Applied whenever the maintenance contractor responds within the pre-defined response time for 3 consecutive times	Incentive value per reduced day per pothole
		Maximum response time for barriers' removal	N/A	N/A	N/A	$250.00	N/A	N/A	N/A	$100.00	Applied whenever the maintenance contractor fails to respond within the pre-defined response time	Penalty value per additional day per barrier	Applied whenever the maintenance contractor responds within the pre-defined response time for 3 consecutive times	Incentive value per reduced day per barrier
		Maximum response time for repairing defective guardrails	N/A	N/A	N/A	$300.00	N/A	N/A	N/A	$100.00	Applied whenever the maintenance contractor fails to respond within the pre-defined response time	Penalty value per additional day per defective guardrail	Applied whenever the maintenance contractor responds within the pre-defined response time for 3 consecutive times	Incentive value per reduced day per defective guardrail

5.2.1.2 *Post-Contract Optimization*

The post-contract optimization featured a multi-objective hierarchical optimization as discussed earlier in the research methodology chapter. It is worth noting that the resilience preparedness model was not applied to the city of Montréal case study given the lack of available demand data. Thus, the system featured all the other performance assessment models except the resilience preparedness. The analysis was categorized according to the multi-assessment dimensions: financial; temporal; spatial; physical; risk; efficiency; and effectiveness. The optimization setup could be displayed in Figure 5.5. The weights of importance for the multi-dimensional assessment indicators are defined in Table **5-12**. The study planning horizon was 25 years. As discussed earlier, the multi-objective hierarchical optimization featured a GAs based optimization engine with the attributes outlined earlier in Table **5-8**. The coordination improvements' optimization results were summarized in terms of the multi-dimensional assessment indicators as opposed to the conventional scenario. A summary of the results is outlined in Table **5-13**. The optimization showed promising results in favor of the fully-coordinated interventions as opposed to the conventional one in terms of (1) number of interventions; (2) disruption time; (3) LCC including direct and indirect costs resulting from the intervention actions; (4) consumed space for undertaking the interventions; (5) assets' reliability; (6) assets' risk of failure; and (7) operating time (free of intervention) time. In order to compute the improvements, the conventional system was modeled using meta-heuristic rules to ensure that the minimum acceptable reliability threshold is met. As shown in Figure 5.6, the reliability of the fully-coordinated intervention program was better with a CIF of 10% compared to the conventional intervention program. Similarly, the risk exposure of the coordinated intervention program showed to be less as it displayed a 10% RIF, shown in Figure 5.10, as opposed to the conventional intervention program. Those savings are a result of the improved reliability. The financial savings, represented through the indirect costs and LCC, are shown in Figure 5.7 and Figure 5.8 respectively. The fully-coordinated intervention program displayed 50% savings in terms of indirect costs compared to the conventional intervention program, implying a fewer number of interventions and less delay time for service disruptions due to combining the interventions of the co-located systems sharing the same spatial location. Moreover, it showed 18% LCC savings compared to the conventional intervention program as a result of combining the intervention actions of the three systems and given the existence of common and joint activities. Similarly, as displayed in Figure 5.9, the fully-coordinated intervention program displayed 12% temporal savings as opposed to the conventional intervention program. Those savings reflect the coordination of the intervention activities such that the common activities have been carried out once instead of n_a or n_s times for the partially-coordinated and conventional intervention scenarios respectively. Furthermore, undertaking the fully-coordinated intervention increased the number of parallel activities, which increased the temporal savings as opposed to the conventional approach in which n_s interventions are separately undertaken for each system. In terms of efficiency and effectiveness, specific conclusions were driven by analyzing the corridor-based results of the fully-coordinated intervention program as opposed to the conventional intervention program. Furthermore, the coordinated intervention program displayed 16% STIF that implies the less amount of consumed space because of the smaller number of corridor revisits.

The fully-coordinated intervention program resulted in a more effective intervention plan in terms of the number of service disruptions carried out for the same corridor. The revisiting schedule represents the frequency of carrying out interventions in the same corridor across the planning horizon, as shown in Figure 5.11. The fully-coordinated intervention program showed to be more efficient in more than 70% of the corridors with a fewer number of interventions. Those savings resulted in temporal and financial savings as well as less end-user service disruption. The coordinated intervention program showed to be 30% more efficient with a fewer number of interventions resulting from the coordination. Furthermore, it displayed a 26% IFF as opposed to the conventional invention program with longer operating times for the systems under study. Based on the pre-defined KPIs' weights of importance, the coordinated intervention program revealed a 15% overall improvement as opposed to the conventional intervention program.

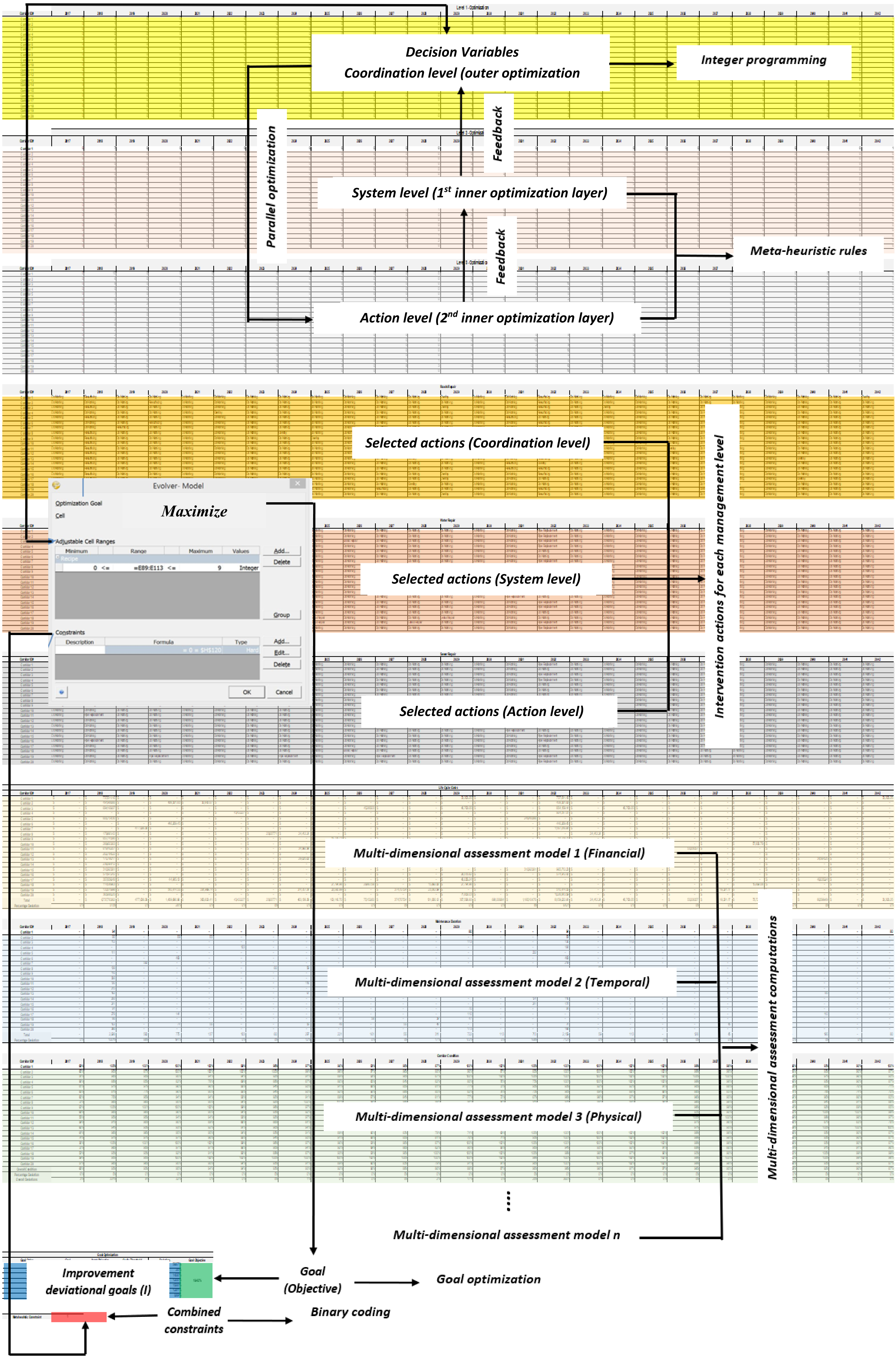


Figure 5.5: *Optimization setup – City of Montreal*

Table 5-12: *Assessment indicators' weights of importance – City of Montreal*

Performance Indicator	Basis	Weights of importance (%)
Time (I_1)	Intervention Duration	10%
Space (I_2)	Intervention Spatial and Interdependency	10%
Cost (I_3)	Life-Cycle Costs	25%
Efficiency (I_4)	Intervention Crew	5%
Effectiveness (I_5)	Intervention Quality	5%
Condition (I_6)	Physical state, Reliability, and LOS	25%
Risk (I_7)	Probability and Consequences of Failure	20%

Table 5-13: *Optimization improvement results – City of Montreal*

Assessment Index/Coordination Scenario	Index	Improvement (%)
Time (I1)	NCR	12%
Space (I2)	STIF	16%
Cost (I3)	LIF	18%
Efficiency (I4)	IEF	30%
Effectiveness (I5)	IFF	26%
Condition (I6)	CIF	10%
Risk (I7)	RIF	10%
Overall Improvement (Z)		***15%***

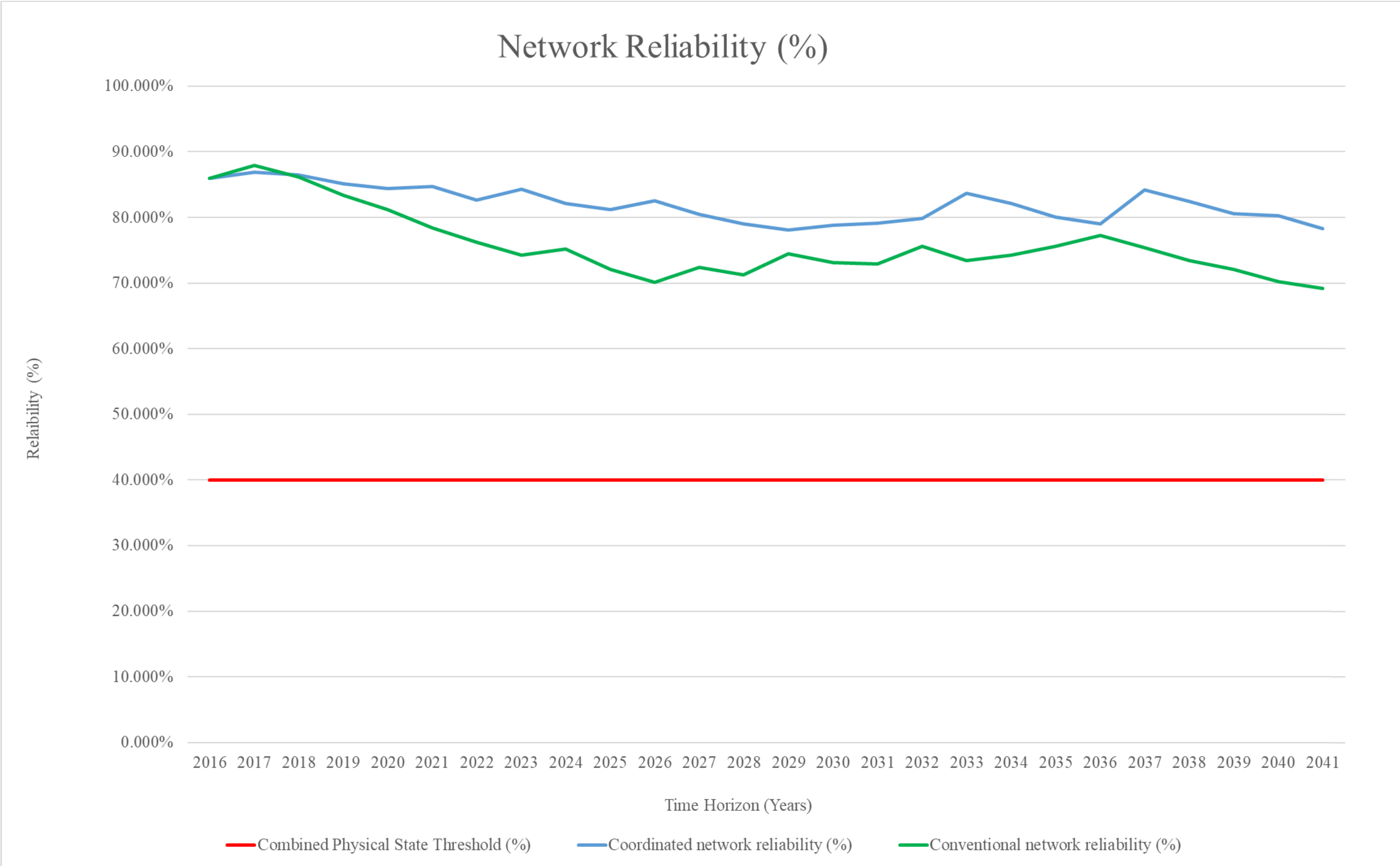


Figure 5.6: *City of Montréal optimization results – Network reliability*

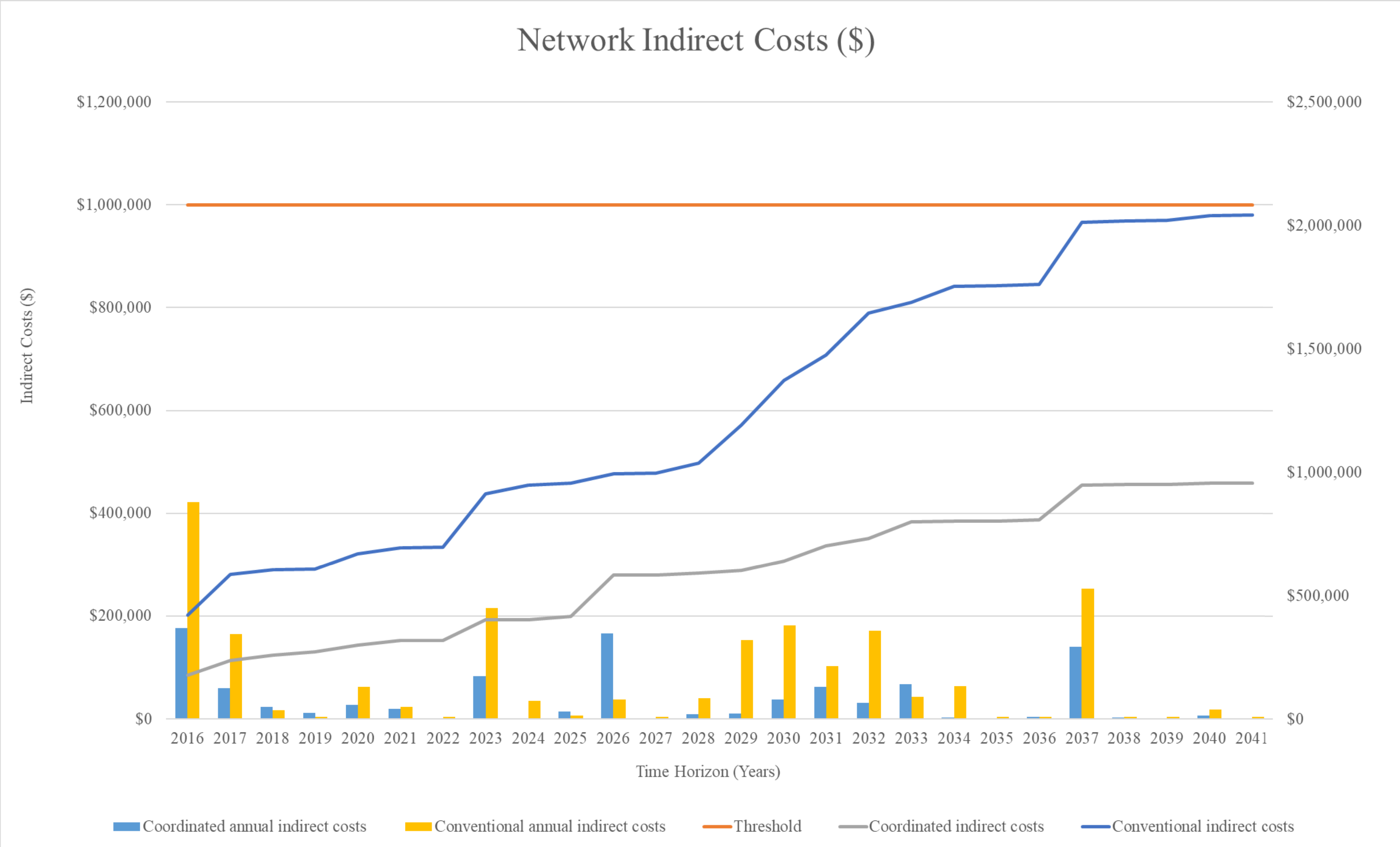


Figure 5.7: *City of Montréal optimization results – Indirect costs*

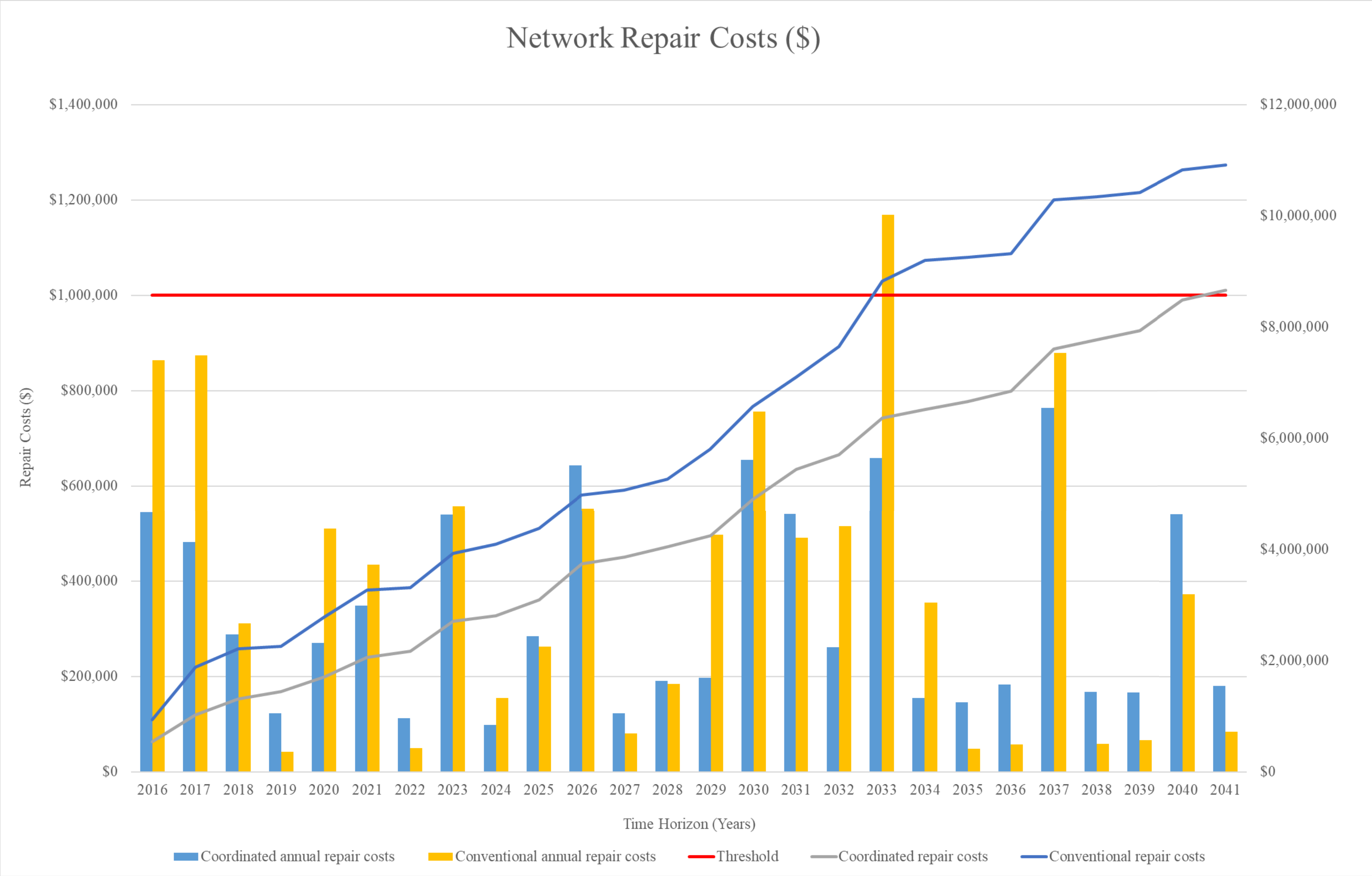


Figure 5.8: *City of Montréal optimization results – Repair cost*

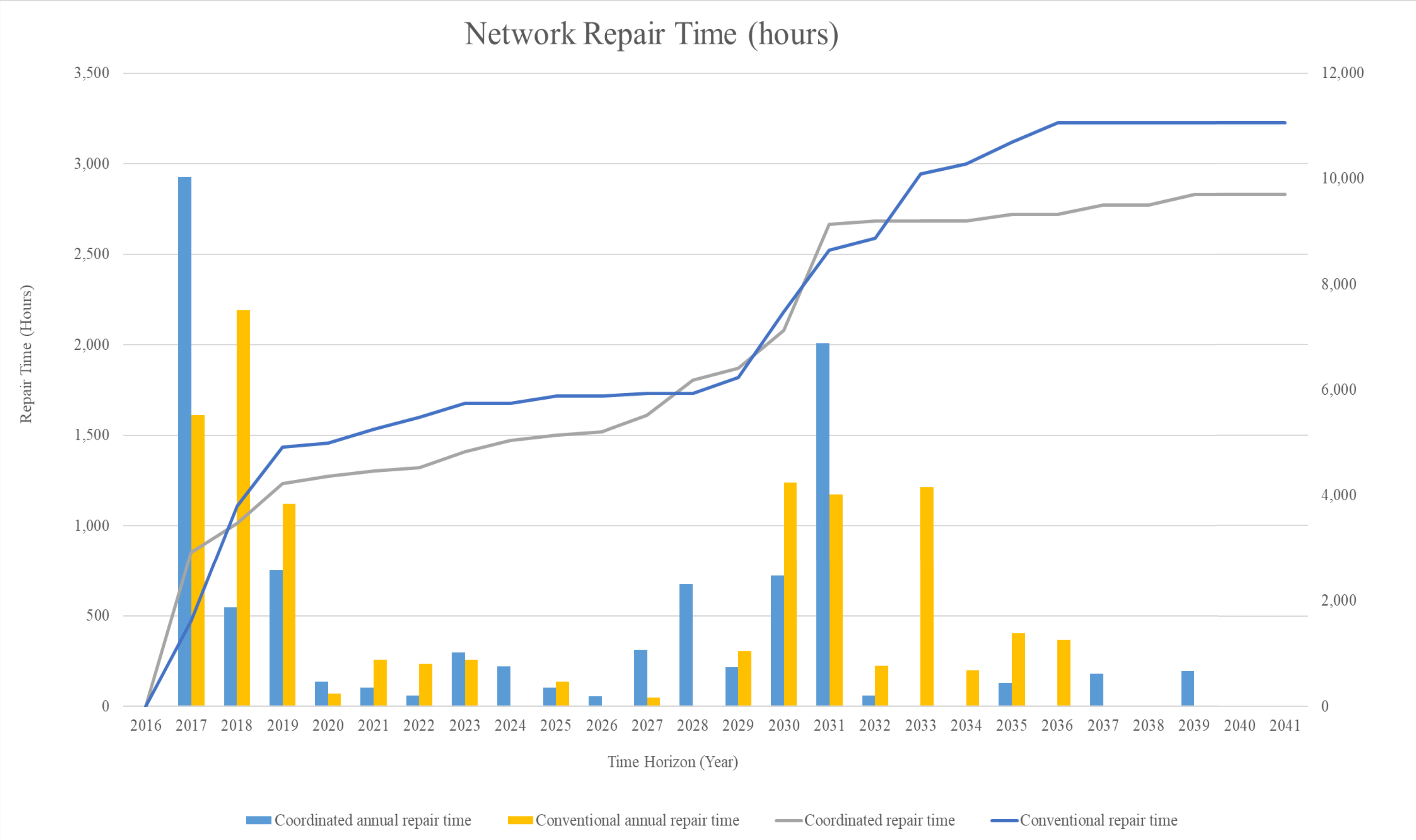


Figure 5.9: *City of Montréal optimization results – Repair time*

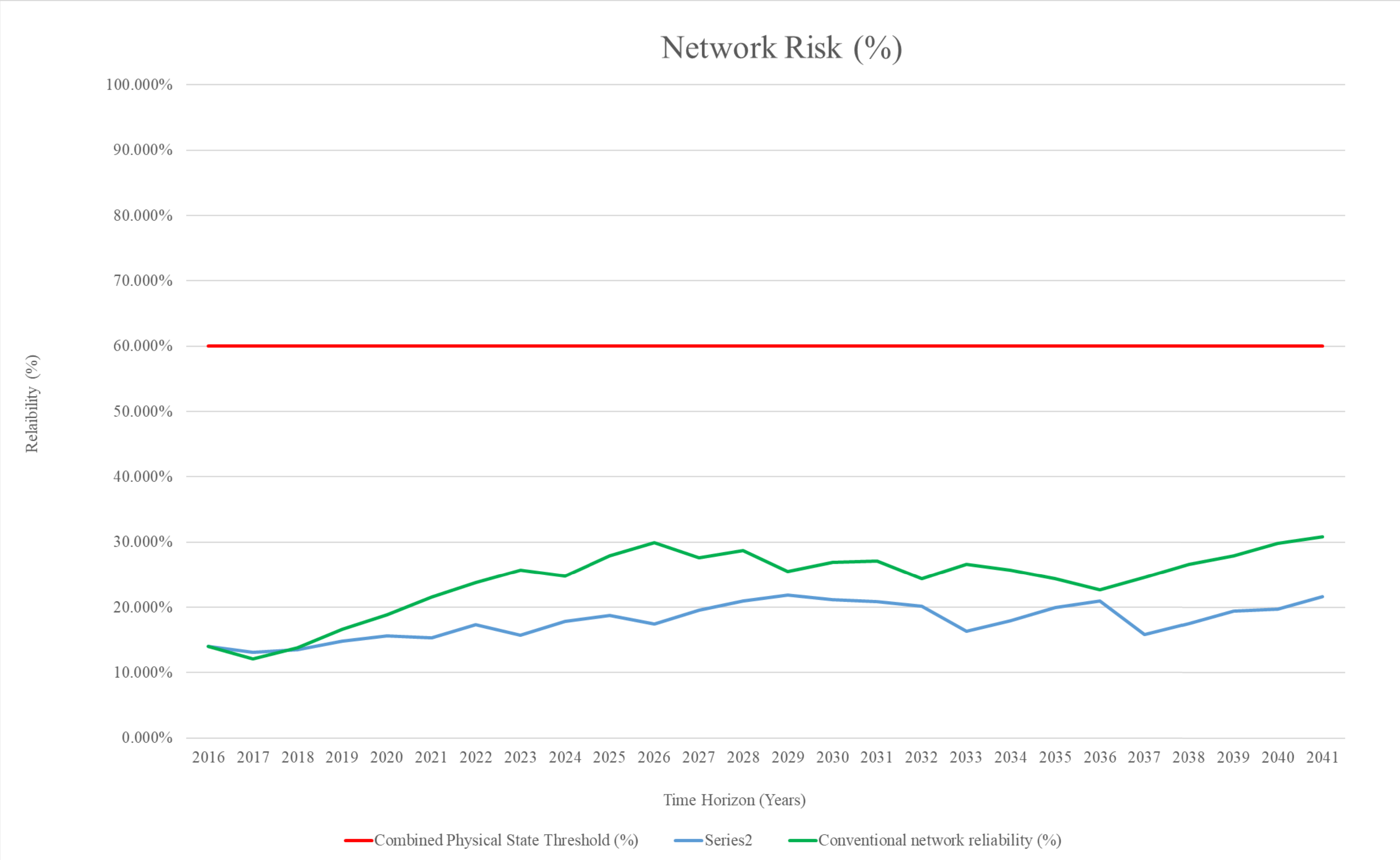


Figure 5.10: *City of Montréal optimization results – Network risk*

Corridor ID #	System	Integration Status	Winning Status	Frequency Difference	2016	2017	2018	2019	2020	2021	2022	2023	2024	2025	2026	2027	2028	2029	2030	2031	2032	2033	2034	2035	2036	2037	2038	2039	2040	2041
8	R	*CONV*		3																										
		COOR																												
	S	*CONV*		3																										
		COOR																												
	W	*CONV*		3																										
		COOR																												

CONV: Conventional Intervention Program
COOR: Fully-coordinated Intervention Program

Figure 5.11: *Sample from the corridor revisiting schedule – City of Montreal*

5.2.2 *Sensitivity Analysis*

Sensitivity analysis is performed to study and verify the sensitivity of the increasing or decreasing the minimally acceptable reliability thresholds on the other KPIs'. It can answer many what-if questions such as: "Should we pay more for enhancing the network reliability?" And if the answer is yes, "what is the cost premium between the proposed intervention program and the optimal intervention program?" The sensitivity analysis was undertaken and four new optimization cases ranging between -20% and +20% with 10% increments were run. After running the optimization on the four scenarios, the improvement deviational variables were computed as outlined in Table **5-14**. Thenceforth, the sensitivity analysis was carried out to compare the cases' improvement deviations variables outcomes with the baseline case and accordingly plot the difference as outlined in Table **5-15**.

The system showed to be very sensitive to changes in the reliability threshold as shown in Table **5-15** and Figure 5.12. For instance, increasing the reliability threshold by 10% revealed 42% additional repair time and 31% additional space, 33% extra repair costs for undertaking additional interventions, 13% reduced efficiency given the extra interventions that were undertaken across the planning horizon, 31% less effectiveness implying less operating time, 30% increase in the average network reliability and risk, and 12% decrease in the overall improvement as opposed to the baseline scenario. Similarly, the other scenarios were carried out and the results were plotted in Figure 5.12. In summary, slight changes in the reliability drastically affect the other KPIs. The repair time and cost showed to be the most sensitive items to the changes in the reliability thresholds. However, the effectiveness showed to be the least sensitive item to the changes in the reliability thresholds.

Table 5-14: *Sensitivity analysis cases – Improvement deviational variables – City of Montreal*

Assessment Index/ Scenario	Index	Baseline Improvement (%)	Case 1 (-20%)	Case 2 (-10%)	Case 3 (10%)	Case 4 (20%)
Time (I1)	NCR	12%	15%	19%	7%	10%
Space (I2)	STIF	16%	20%	22%	11%	15%
Cost (I3)	LIF	18%	21%	24%	12%	17%
Efficiency (I4)	IEF	30%	39%	33%	26%	21%
Effectiveness (I5)	IFF	26%	21%	23%	18%	25%
Condition (I6)	CIF	10%	6%	9%	13%	15%
Risk (I7)	RIF	10%	6%	9%	13%	15%
Overall Improvement (Z)		***15%***	14%	17%	13%	16%

Table 5-15: *KPIs' summary results for sensitivity analysis - City of Montréal*

Assessment Index/ Scenario	Index	Case 1 (-20%)	Case 2 (-10%)	Baseline Improvement (%)	Case 3 (10%)	Case 4 (20%)
Time (I1)	NCR	25%	58%	0%	-42%	-17%
Space (I2)	STIF	25%	38%	0%	-31%	-6%
Cost (I3)	LIF	17%	33%	0%	-33%	-6%
Efficiency (I4)	IEF	30%	10%	0%	-13%	-30%
Effectiveness (I5)	IFF	-19%	-12%	0%	-31%	-4%
Condition (I6)	CIF	-40%	-10%	0%	30%	50%
Risk (I7)	RIF	-40%	-10%	0%	30%	50%
Overall Improvement (Z)		-1%	16%	0%	-12%	8%

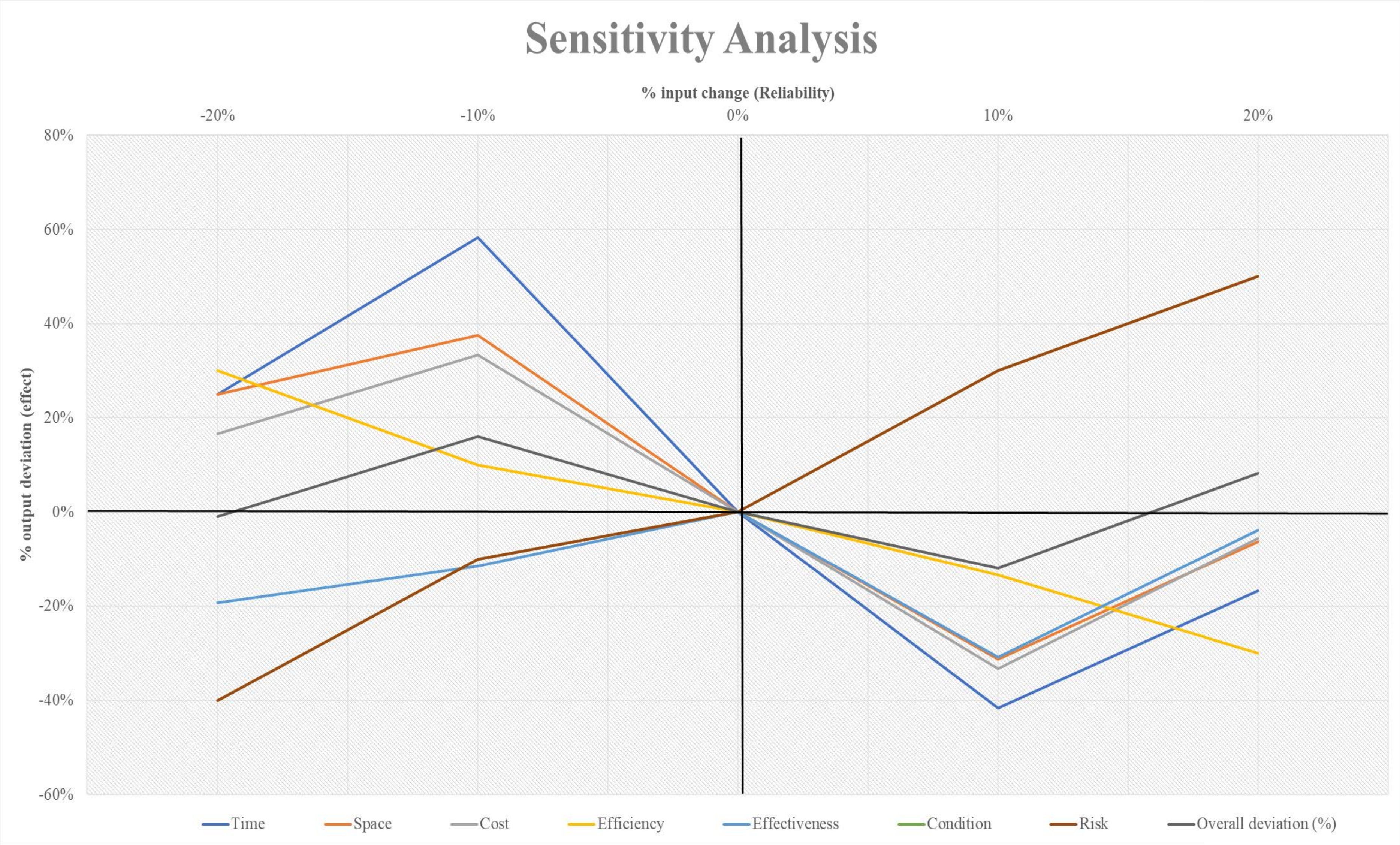


Figure 5.12: *Sensitivity analysis results – City of Montreal*

5.2.3 *Model Validation*

Given the fact that the city of Montréal does not apply coordinated asset management and only applies conventional (system-based) management, the conventional system results were compared with the city's indicators, discussed in Appendix B. In order to validate the system, an interview with Mr. Normand Hachey, *Chef de division plan directeur*, was conducted to validate the overall network results as well as the unit costs and rates. After a thorough discussion with Mr. Hachey, it was pointed out that the city does not plot the same indicators used in this study. For instance, the city's consequences of failure, as a part of the risk indicator, are calculated from the actual claims/cases they experience due to any asset failure or impacts of rehabilitation works, which differs from the system's risk indicator. Thus, the results of the comparison will not match and thus, the risk indicator was excluded. Another example is the repair time. The city does not directly plot the intervention time as most of the repair and rehabilitation works are subcontracted and thus, the other party is contractually responsible for that. Similarly, some indicators are not considered in the city's planning such as; the intervention's spatial extent, intervention schedule efficiency and effectiveness. For those reasons, two out of eight models namely; financial and reliability were compared and validated with the city officials. To undertake the financial analysis, the equivalent uniform annual expenditures were compared to the system outcome. Furthermore, the system costs were exponentially increased to represent the whole network, given the fact that the case study was only applied to 9 km stretch. Thenceforth, the equivalent uniform annual expenditures were divided by the network length to compute a unit cost per km. The overall financial difference for the three assets was 14% in favor of the conventional system as outlined in Table **5-16**. The difference could be broken down into 20% for the roads, 13% and 10% for the water and sewer pipes. Those differences were because of the different activities considered in the analysis. For instance, the potholes repair, salt application on roads, and ice removal activities were considered in the city's costs and were not considered in the study. Furthermore, the overall network reliability of the three assets within the system was 20.7% less than the overall network reliability of the city. The difference could be broken down into 29.2% for the roads, 11% and 16% for the water and sewer pipes. In summary, the system spent 14% extra costs to improve the network reliability of the three systems by 20.7% compared with the city's network relaibility. For the reliability model, the typical deterioration curves of the three assets in one corridor were compared with the city deterioration curves as displayed in Figure 5.13, Figure 5.14, and Figure 5.15 for roads, water, and sewer pipes respectively. It is worth noting that the positive effect of the interventions was validated separately and there were no major differences between the system and the city's assumption. As displayed in Figure 5.13, the average absolute difference in the roads' deterioration was 5% in favor of the city's deterioration. This difference took place because the system considered the impact of several factors (i.e. extreme weather conditions), which speeded the deterioration of the assets and thus, resulted in that difference. For the water and sewer networks, there were negligible differences of 3% between the two curves given the long service life of those assets as shown in Figure 5.14 and Figure 5.15.

Table 5-16: *Financial model validation – City of Montreal*

System/Asset	Road	Water	Sewer	Network
City ($/Km)	$ 27,000.00	$ 30,000.00	$ 18,000.00	$ 75,000.00
System ($/Km)	$ 32,400.00	$ 33,900.00	$ 19,800.00	$ 85,500.00
Difference (City – System)	-$5,400	-$3,900	-$1,800	-$10,500
Difference (%)	20%	13%	10%	14%
Network Reliability - City (%)	55.8%	71%	73%	64.8%
Network Reliability – System (%)	85%	82%	89%	85.5%
Network Reliability Difference (System - City)	29.2%	11%	16%	20.7%

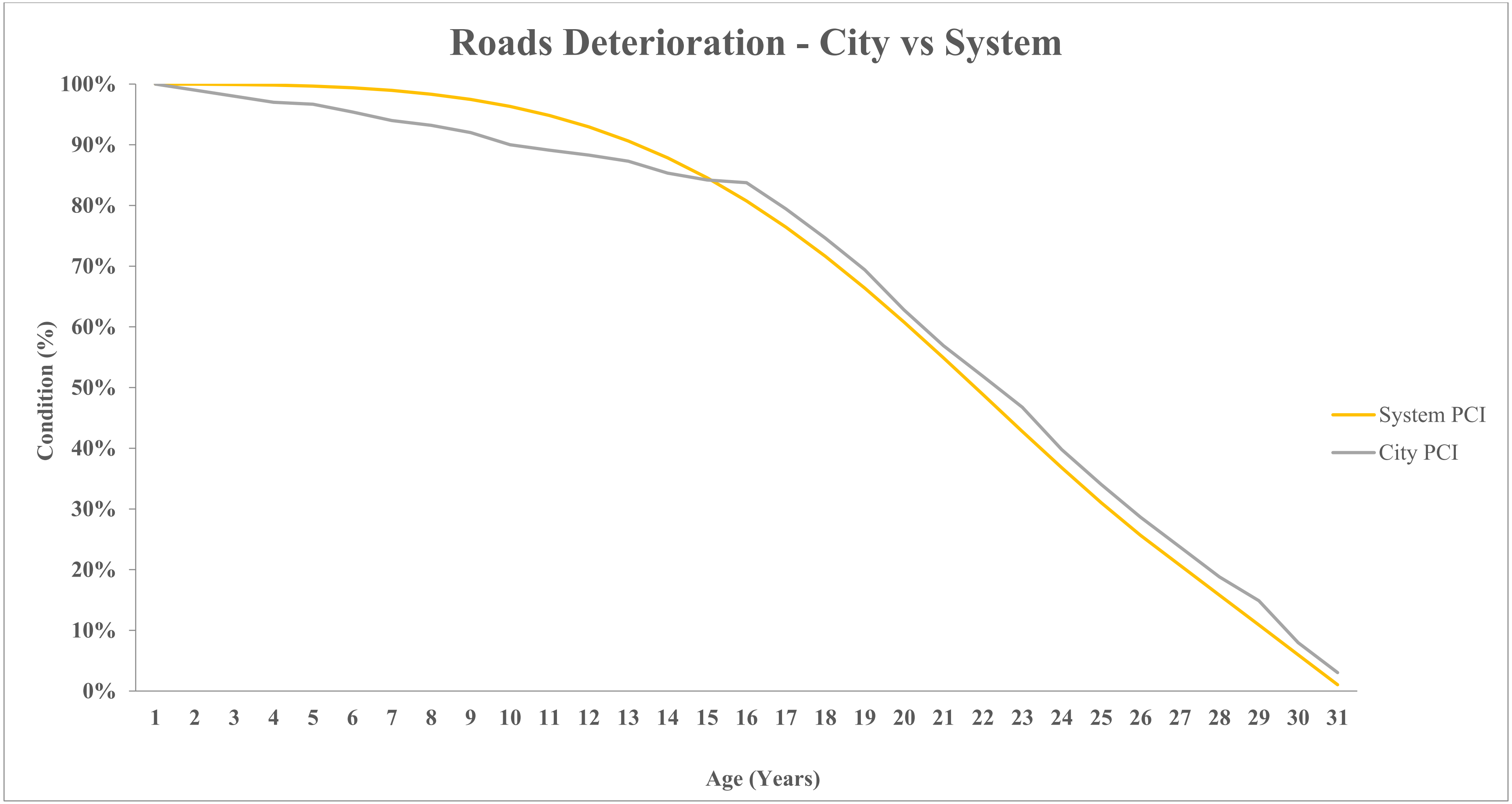


Figure 5.13: *Roads' deterioration and POF curves – city vs system*

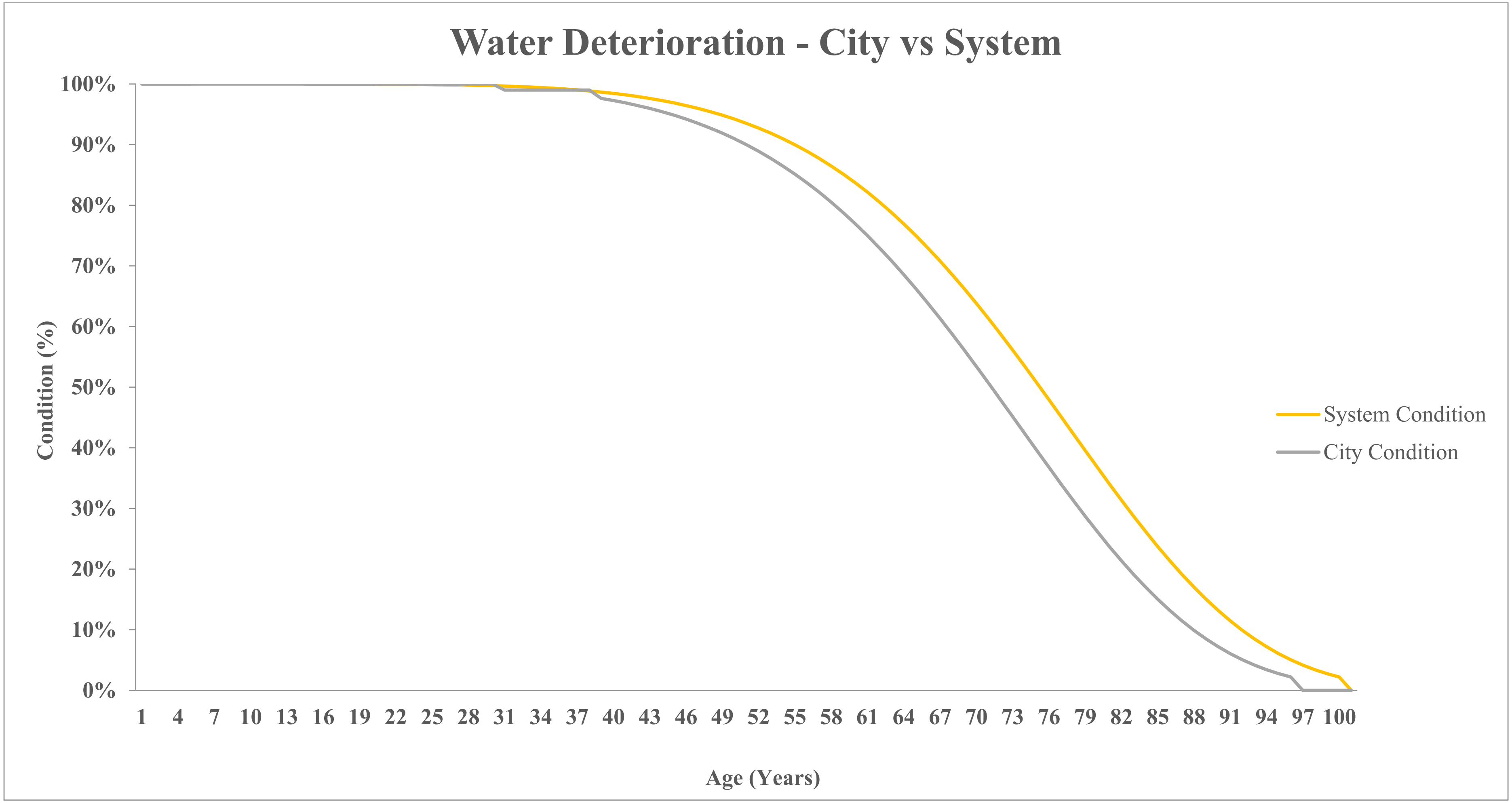


Figure 5.14: *Water pipes' deterioration and POF curves – city vs system*

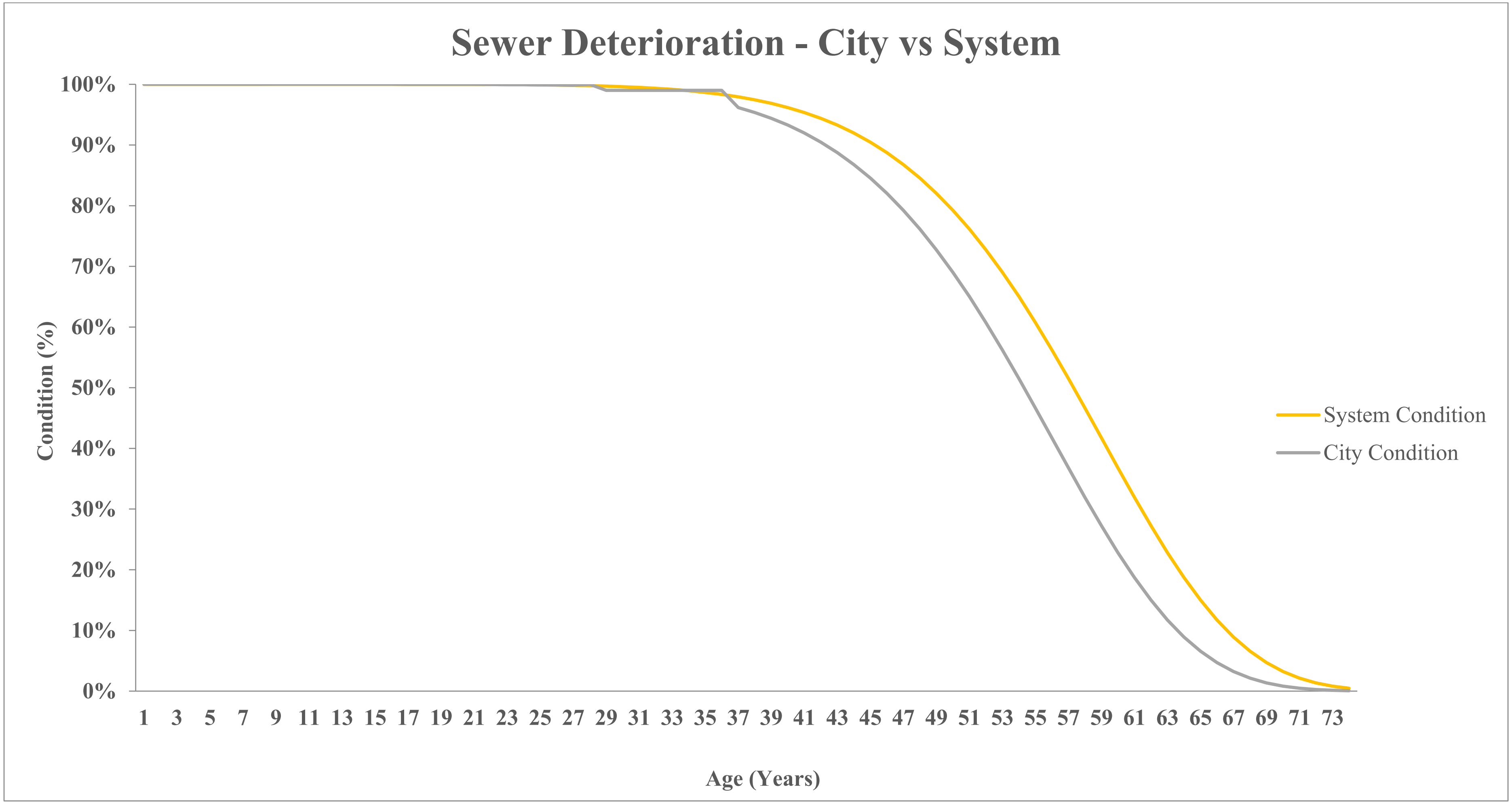


Figure 5.15: *Sewer pipes' deterioration and POF curves – city vs system*

5.3 Town of Kindersley Case Study

A 53 km stretch from the town of Kindersley was selected for analysis. In this case, the system set the penalties and incentives' values to "0" to display the capability of running the system for in-house maintenance. The optimization model was run on the post-contract optimization mode across 25 years planning horizon using REMSOFT software integrated with MOSEK linear programming optimization engine. The post-contract optimization results aim at reaching an exact solution, using linear goal optimization, and attaining the intervention schedule/plan for eight scenarios as follows: (1) roads' conventional optimization that reaches an exact solution (intervention plan) for the roads network; (2) water pipes' conventional optimization that reaches an exact solution (intervention plan) for the water network; (3) sewer pipes' conventional optimization that reaches an exact solution (intervention plan) for the sewer network; (4) combined conventional optimization that reaches an exact solution (intervention plan) for the roads, water, and sewer networks; (5) roads and water pipes' partial optimization integrated with the sewer pipes' conventional optimization that reaches an exact solution (intervention plan) for the coordinated network; (6) roads and sewer pipes' partial optimization integrated with the water pipes' conventional optimization that reaches an exact solution (intervention plan) for the coordinated network; (7) sewer and water pipes' partial optimization integrated with the roads' conventional optimization that reaches an exact solution (intervention plan) for the coordinated network; and (8) roads, water, and sewer pipes' full coordination optimization integrated with the roads' reconstruction that reaches an exact solution (intervention plan) for the coordinated network. Further details about the optimization scenarios will be discussed later in the upcoming sub-section. The results' discussion will be divided into three sub-sections as follows: (1) optimization results; (2) sensitivity analysis; and (3) model validation. The optimization results will discuss post-contract optimization results for the eight scenarios. Hence after, the sensitivity analysis aims at analyzing the impact of changing the reliability KPI threshold on the other KPIs; and comparing it with the baseline scenario. Finally, the optimization model results will be compared and validated with the other study from which the data was extracted from.

5.3.1 *Optimization Results*

The optimization results will be categorized to conventional, partially and fully-coordinated scenarios as displayed in Table **5-17**. The results of each scenario will be discussed and analyzed separately in the subsequent sub-sections. It is worth mentioning that the planning horizon of this study was 25 years and a 2% interest rate was used for the Net Present Worth (NPW) and Equivalent Uniform Annual Costs (EUAC) calculations. The weights of importance for the multi-dimensional assessment indicators are defined in Table 3-19. It is worth noting that the resulting intervention schedules along with their analysis (i.e. spatial consumption, corridor re-visiting schedule) for the eight scenarios are displayed in Appendix D.

5.3.1.1 *Conventional Optimization Results*

The conventional optimization aims at reaching an exact optimal intervention plan for each asset separately across the 25 years planning horizon. Scenarios 1 through 3 represent the roads, water, and sewer networks respectively. The combined conventional intervention plan of the three networks is presented in scenario 4. The conventional results are the basis of computing the improvement deviational variables in the partially and fully-coordinated scenarios as will be discussed later.

Table 5-17: *Town of Kindersley optimization scenarios*

Scenario ID #	Coordination	Scenario Name	Scenario Description
Scenario 1	Conventional	Roads' conventional optimization	Exact solution for the intervention plan of the roads network
Scenario 2		Water pipes' conventional optimization	Exact solution for the intervention plan of the water network
Scenario 3		Sewer pipes' conventional optimization	Exact solution for the intervention plan of the sewer network
Scenario 4		Combined conventional for roads, water, and sewer	Exact solution for the intervention plan of the roads, water, and sewer networks
Scenario 5	Partially-coordinated	Roads and water pipes' partially-coordinated optimization	Exact solution for the intervention plan of the partially coordinated roads and water networks along with the conventional sewer network results
Scenario 6		Roads and sewer pipes' partially-coordinated optimization	Exact solution for the intervention plan of the partially coordinated roads and sewer networks along with the conventional water network results
Scenario 7		Water and sewer pipes' partially-coordinated optimization	Exact solution for the intervention plan of the partially coordinated water and sewer networks along with the conventional roads network results
Scenario 8	Fully-coordinated	Roads, water and sewer pipes' fully-coordinated optimization	Exact solution for the intervention plan of the fully- coordinated roads, water and sewer networks along with the roads' reconstruction

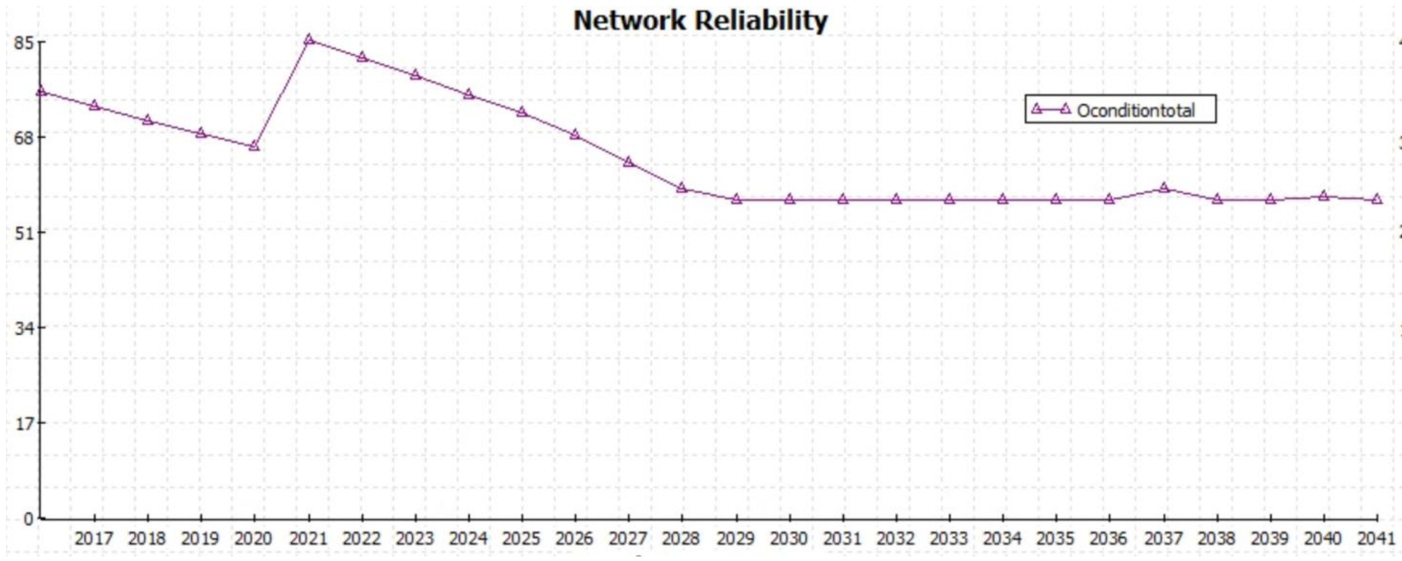
A. Scenario 1 (Conventional roads)

This scenario was carried out on the roads network. MOSEK linear optimization engine was used to reach an exact optimal intervention plan that meets the pre-defined contractual KPIs' thresholds across the planning horizon, as highlighted previously in sub-section 5.2.1.1. The objective of the roads' conventional optimization was maximizing the improvement deviational variables across the planning horizon as discussed in Equation 3.109. The constraints were meeting the unacceptable performance threshold defined earlier in Equations 3.111 and 3.112. The variables were the optimal intervention actions that need to be taken for each corridor at each point of time across the planning horizon as highlighted earlier in Equation 3.108 (i.e. corridor 10 requires a resurfacing in year 4). Given the high frequency of undertaking preventive road maintenance activities such as; crack sealing, potholes repair, the model was analyzed for two cases: (1) road intervention activities including crack sealing; and (2) road intervention activities excluding crack sealing. For the 1st case of road intervention activities including crack sealing, the optimization results could be summarized in Table **5-18** and Figure **5.16**. The results displayed a total of 766 intervention actions split into 489 for crack sealing, 103 for micro surfacing, 13 patching, and 184 for reconstruction. It is obvious that 75% of the intervention actions were for repair and rehabilitation as opposed to 25% for reconstruction. This distribution is because the network was in a very good condition state and undertaking preventive maintenance actions will preserve the corridors' reliability across their planned service lives. The average number of revisits for each corridor was 6 times, which is escalated due to the regular crack sealing as will be displayed in the results of the upcoming case. The average number of interventions per year was 31 interventions for the 125 corridors, which results in an average disruption ratio of 25%. This ratio represents the average annual number of corridors by which an intervention, whether minor or major, will be undertaken, divided by the total number of corridors. The more the disruption factor is, the more the public nuisance is. As shown in Figure **5.16** (A), the overall roads network was in a very good initial reliability of 78%. After running the optimization for 25 years, the reliability dropped to 57% because most of the roads were at the end of their service lives after 25 years and the system was budget-constrained. So, the optimal fund allocation was the resulting one that keeps the roads operational with 57% reliability. Furthermore, as a result of the reduced reliability, the risk index increased from 24% to 43% as displayed in Figure **5.16** (B). The annual intervention time could be displayed in Figure **5.16** (C). The intervention program resulted in 3 million repair hours over the 25 years with an average of 2,300 repair hours per km per year. Similarly, the annual intervention space could be displayed in Figure **5.16** (D). The intervention program resulted in 250,000 m^2 repair space over the 25 years with an average of 3.7 km per year. The annual intervention costs for repair, rehabilitation and reconstruction could be displayed in Figure **5.16** (E). The breakdown of the repair and rehabilitation costs could be displayed in Figure **5.16** (F). Furthermore, the annual reconstruction costs could be displayed in Figure **5.16** (G). The intervention program resulted in NPW of $13.3 million, equivalent to an EUAC of $683,000, for the repair, rehabilitation, and reconstruction of the 53 km of Kindersley's roads' network. Those costs were broken-down to 13% for repair and rehabilitation, amounting $1.8 million over the 25 years planning horizon, and 87% for reconstruction, amounting $11.5 million over the 25 years planning horizon. The average annual expenditures were $12,800 $/year/km.

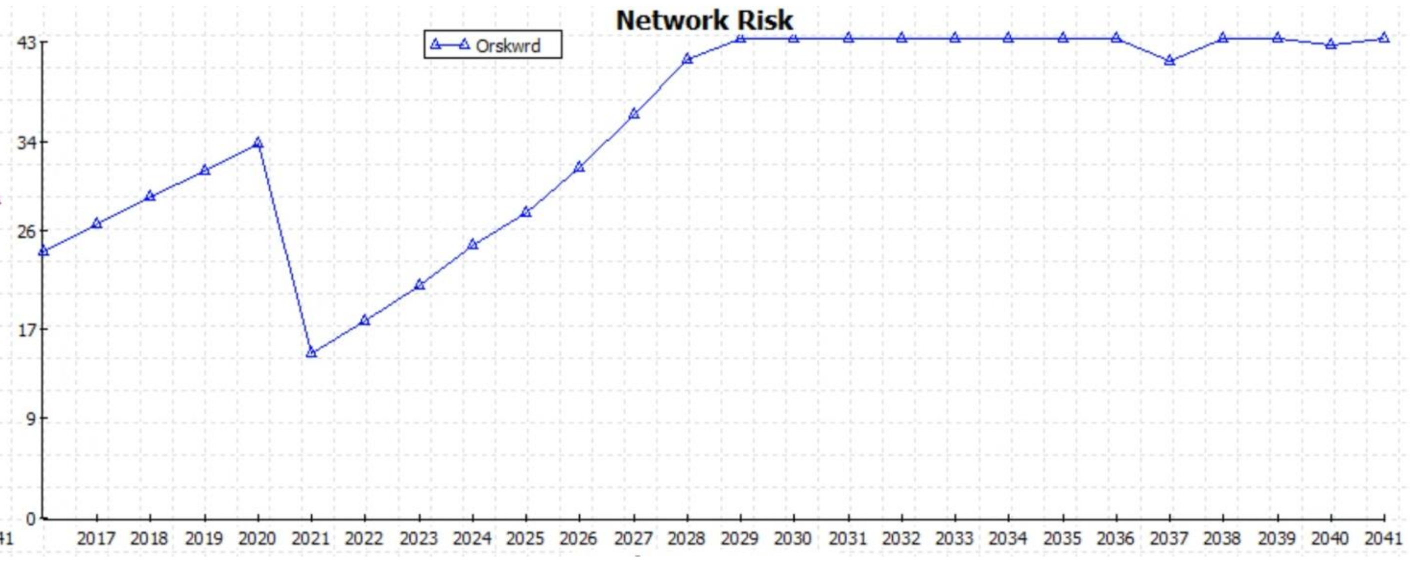
For the 2nd case of road intervention activities excluding crack sealing, the optimization results could be summarized in Table **5-18** and Figure **5.17**. The results displayed a total of 444 intervention actions across the 25 years planning horizon, which is 42% less than the other case with crack sealing. The intervention activities were split into 55% for repair and rehabilitation and 45% for reconstruction. This distribution is because the network started in a very good condition state and needed to be replaced given the lengthy planning horizon, which is nearly equal the service life of the roads. Thus, 45% of the actions were for resurfacing and reconstructing the deteriorated roads and the other 55% were for preserving the existing roads across their planned service lives. The average number of revisits for each corridor was 3 times, which is fair for undertaking two minor activities and one resurfacing or reconstruction activity across the 25 years planning horizon. The average number of interventions per year was 17 interventions for the 125 corridors, which results in an average disruption ratio of 14%. The results of this case are 44% less than the other case with crack sealing due to the exclusion of almost 322 interventions across the planning horizon, which is equivalent to 13 interventions per year. As shown in Figure **5.17** (A), the overall roads network was in a very good initial reliability of 78%. After running the optimization for 25 years, the reliability dropped to 69%. because most of the roads were at the end of their service lives after 25 years and the system was budget-constrained. So, the optimal fund allocation was the resulting one that keeps the roads in an acceptable operational state of 69%. The results of this case were 21% better than the other case with crack sealing even though the average condition was so close with 65% for the case with crack sealing versus 67% for the case without crack sealing. Furthermore, as a result of the reduced reliability, the risk index increased from 24% to 31% as displayed in Figure **5.17** (B). The annual intervention time could be displayed in Figure **5.17** (C). The intervention program resulted in 3.6 million repair hours over the 25 years with an average of 2,700 repair hours per km per year. The repair time for this case was 17% more than the repair time of the crack sealing included case because of the lengthy reconstruction activities that are undertaken in the 2nd case. Furthermore, the extra repair time resulted in a 21% better reliability as discussed earlier. Similarly, the annual intervention space could be displayed in Figure **5.17** (D). The intervention program resulted in 285,000 m^2 repair space over the 25 years with an average of 3.6 km per year. The space consumption is 14% more than the crack sealing included case because the reconstruction activities consume more space compared to other preventive maintenance actions. The annual intervention costs for repair, rehabilitation and reconstruction could be displayed in Figure **5.17** (E). The breakdown of the repair and rehabilitation costs could be displayed in Figure **5.17** (F). Furthermore, the annual reconstruction costs could be displayed in Figure **5.17** (G). The intervention program resulted in NPW of $16 million, equivalent to an EUAC of $817,000, for the repair, rehabilitation, and reconstruction of the 53 km of Kindersley's roads' network. Those costs were broken-down to 22% for repair and rehabilitation, amounting $3.5 million over the 25 years planning horizon, and 78% for reconstruction, amounting $12.5 million over the 25 years planning horizon. The average annual expenditures were $14,400 $/year/km, which is 14% more than the crack sealing included case because of the extra costs associated with reconstructing the roads.

Table 5-18: *Scenario 1 - Optimization summary results – with vs without crack sealing*

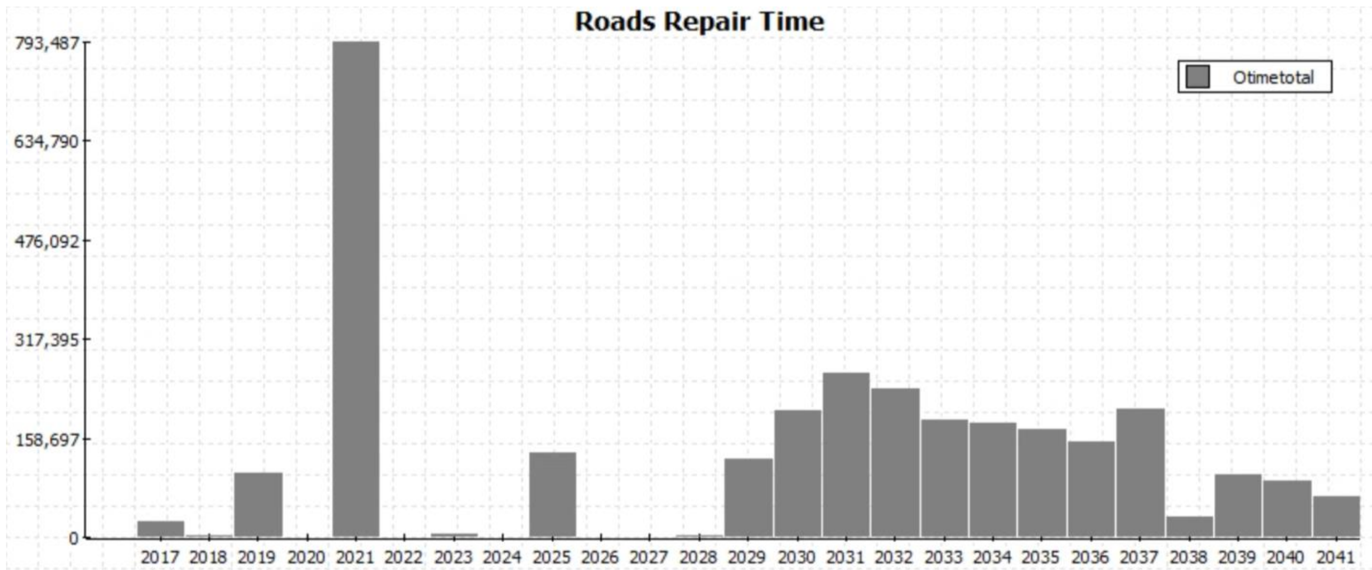
KPI	Roads (with crack sealing)	Roads (without crack sealing)	Difference	Difference (%)
Time (hours)	3,090,887	3,620,580	-529,693	-17%
Space (m^2)	250,009	285,054	-35,045	-14%
Cost – Equivalent Uniform Annual Cost (EUAC) ($)	$683,249	$817,260	-134,011	-20%
Cost – Net Present Worth (NPW) ($)	$13,339,373	$15,955,745	-2,616,372	-20%
Condition (%)	65%	67%	-2%	-3%
Risk (%)	35%	33%	2%	6%
# of intervention actions	766	444	322	42%
Time per km per year (hours/km/year)	2,333	2,733	-400	-17%
Cost per km per year ($//km/year)	$12,891.48	$15,420.00	-2,529	-20%
Average repair length per year (km/year)	3.7	3.6	0.10	3%
Average number of interventions per year	30.64	17.76	13	42%
Ratio of interventions per year - number of annual interventions/number of corridors (%)	25%	14%	11%	44%



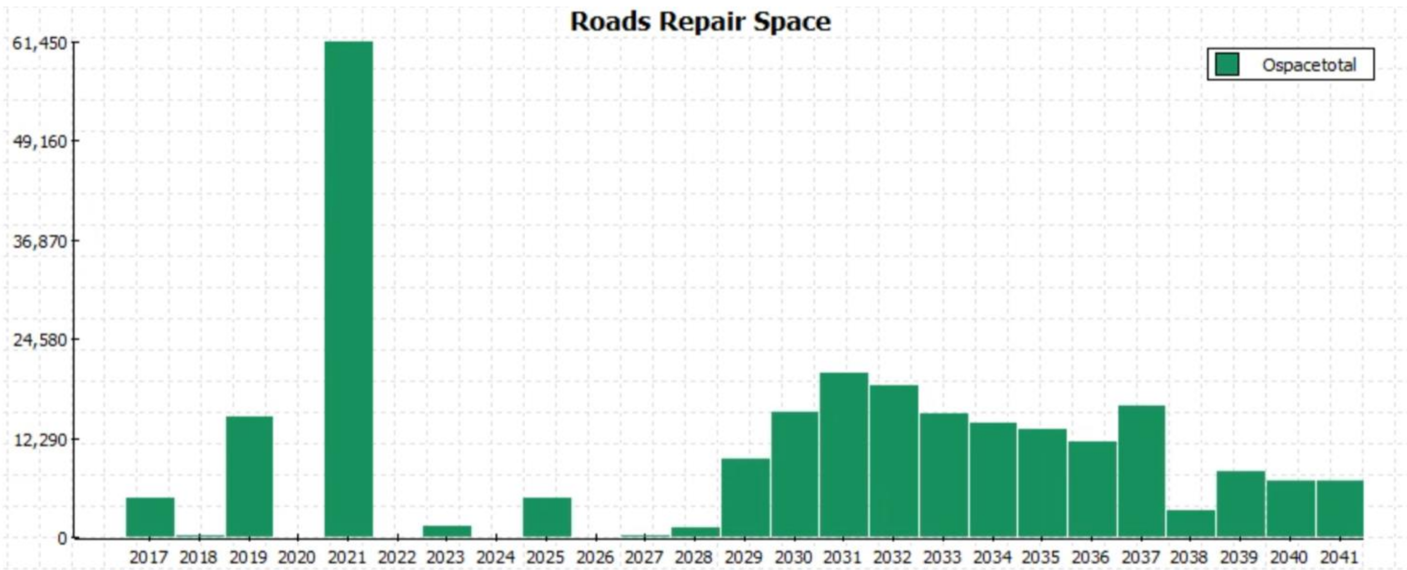
A – *Network reliability*



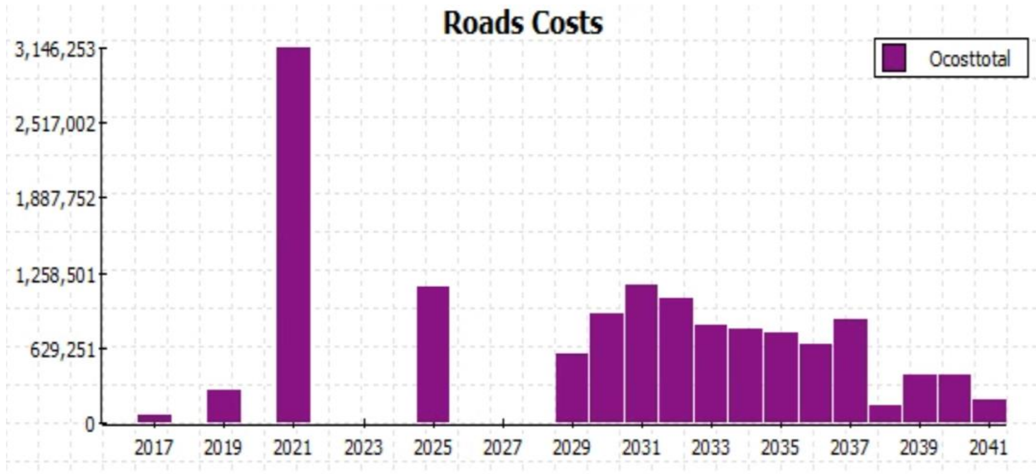
B – *Network risk*



C – *Network repair time*

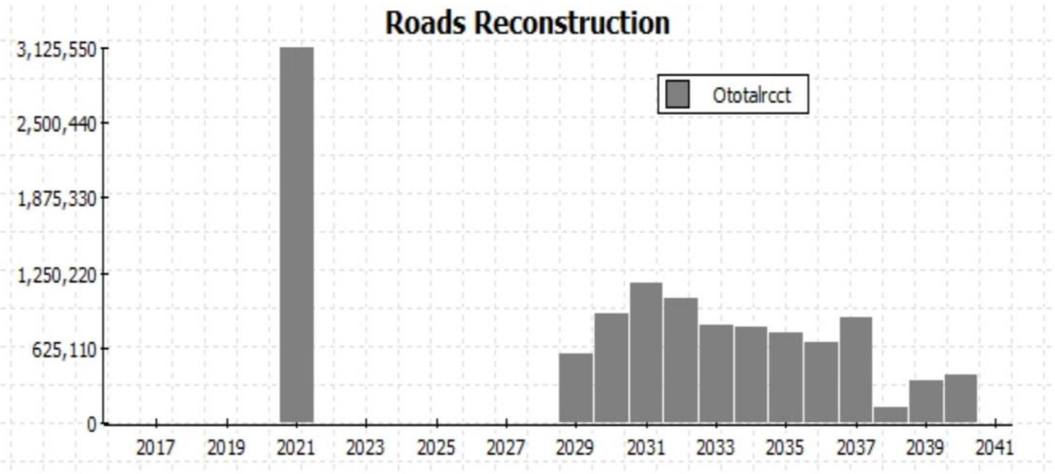


D – *Network space*



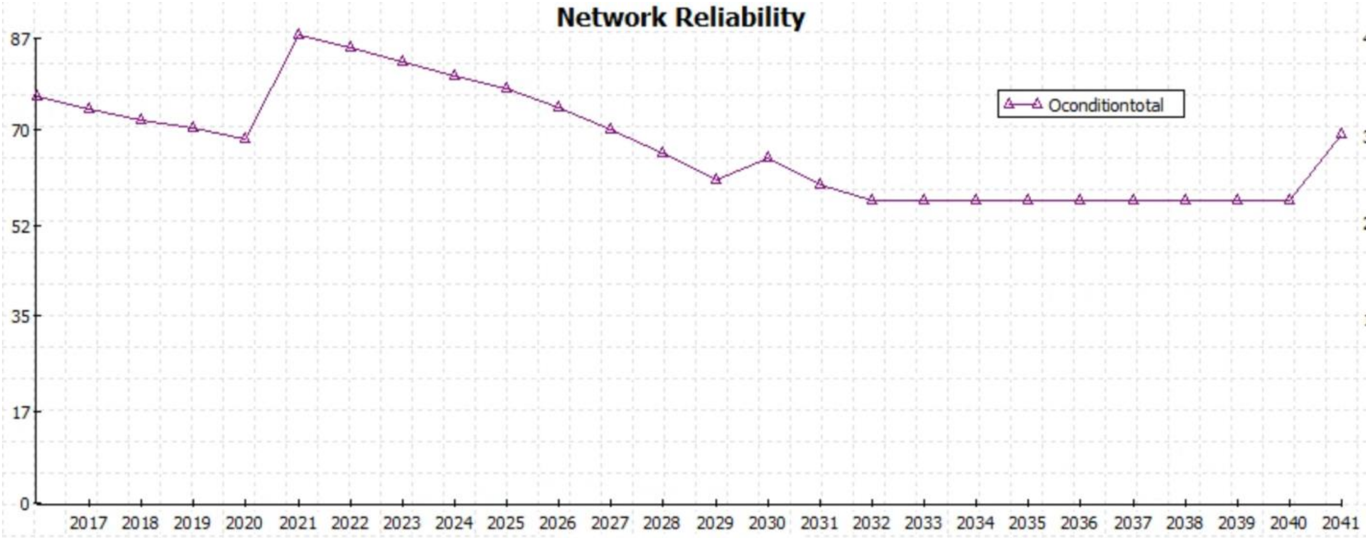
E – *Network repair, rehabilitation, and reconstruction*

F – *Network preventive and rehabilitation costs*

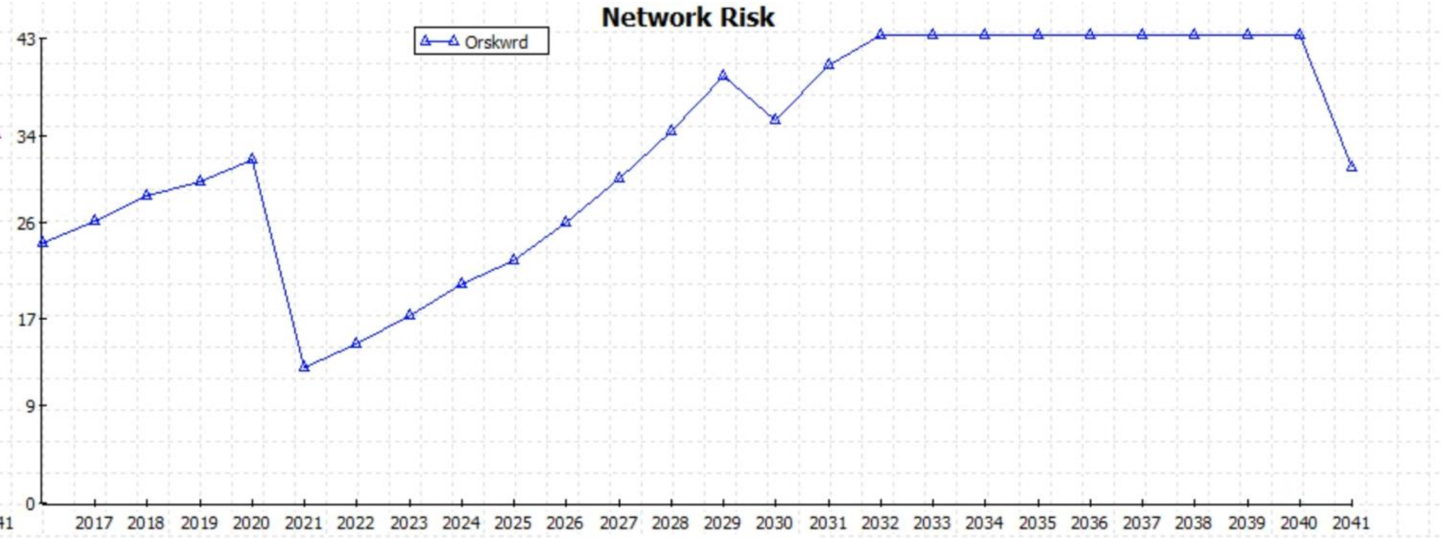


G – *Network reconstruction costs*

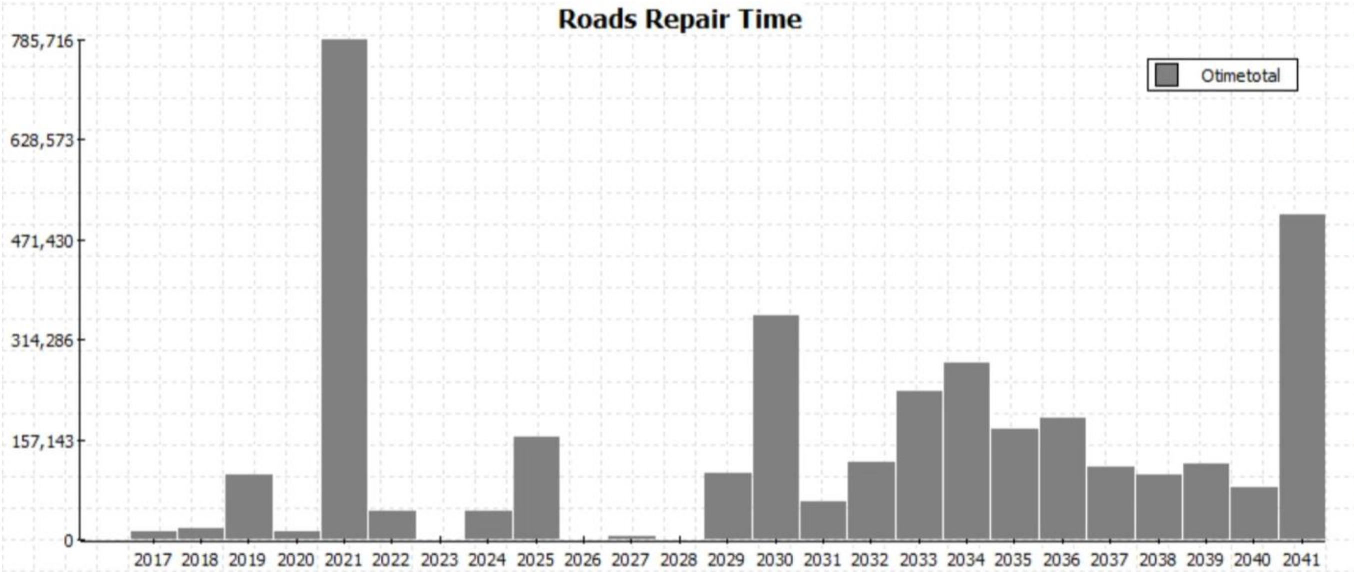
Figure 5.16: *Scenario 1 (with crack sealing) – MOSEK Optimization results*



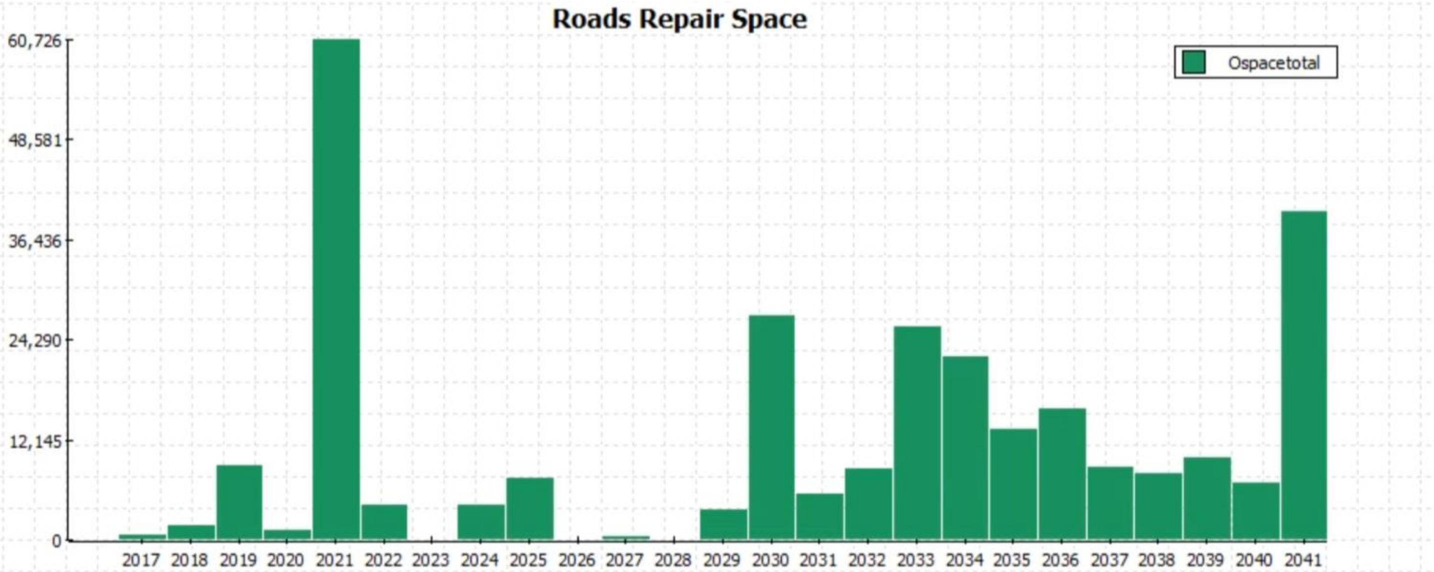
A – *Network reliability*



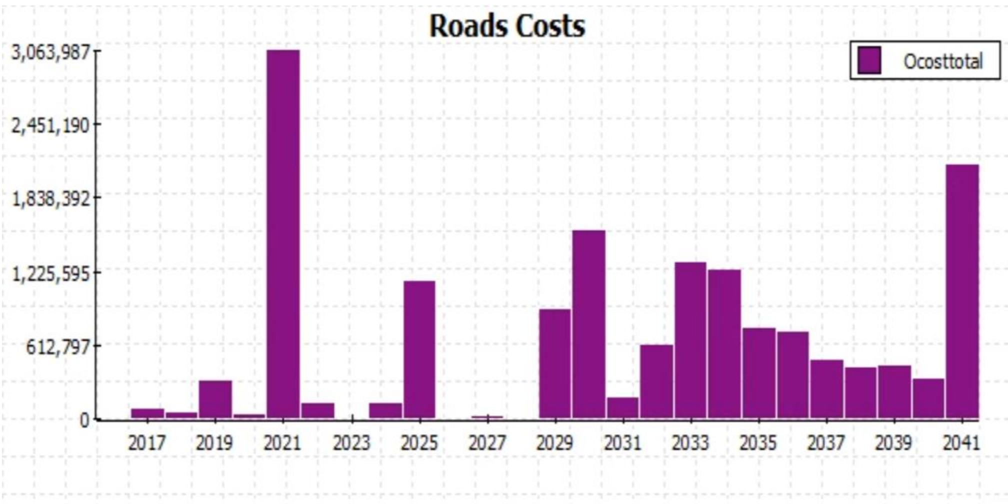
B – *Network risk*



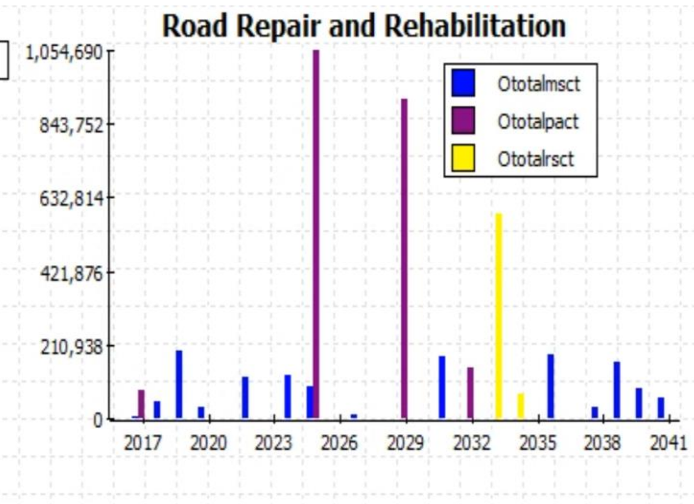
C – *Network repair time*



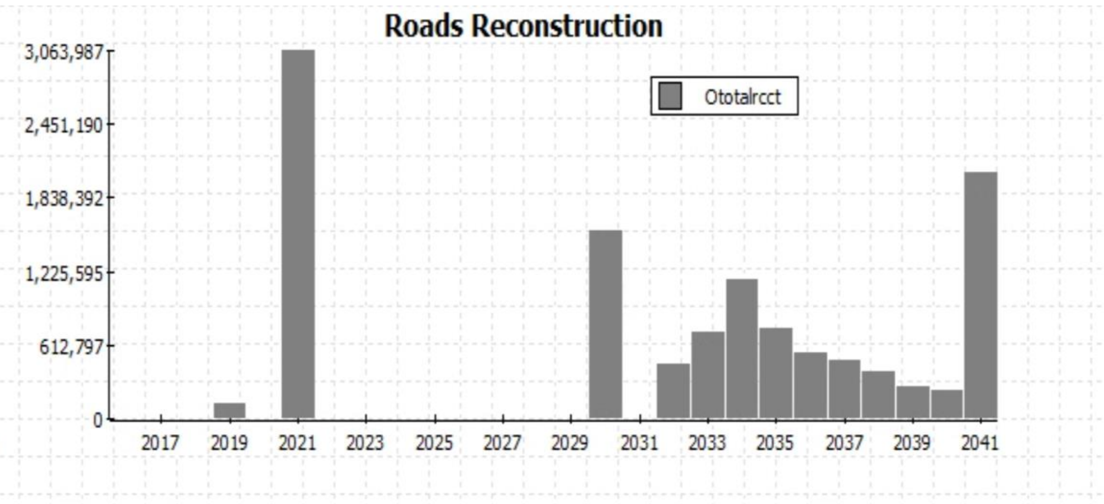
D – *Network space*



E – *Network repair, rehabilitation, and reconstruction*



F – *Network preventive and rehabilitation costs*



G – *Network reconstruction costs*

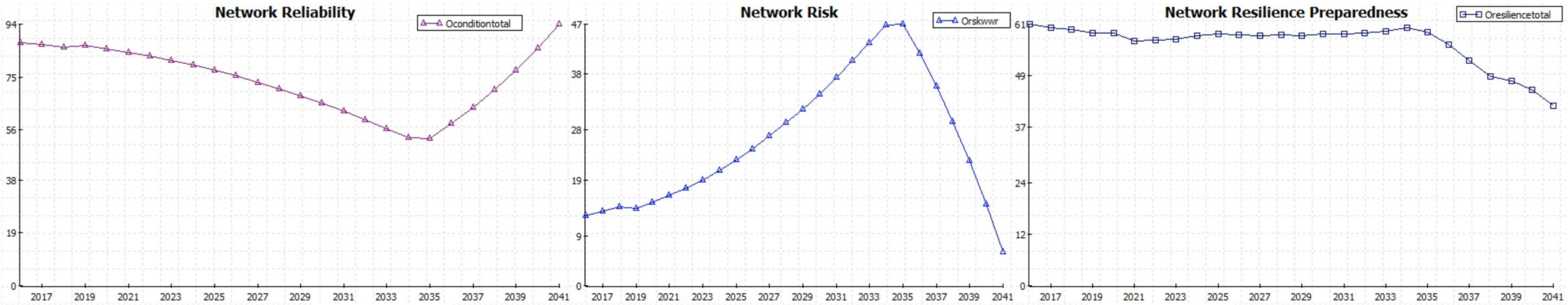
Figure 5.17: *Scenario 1 (without crack sealing) – MOSEK Optimization results*

B. Scenario 2 (Conventional water)

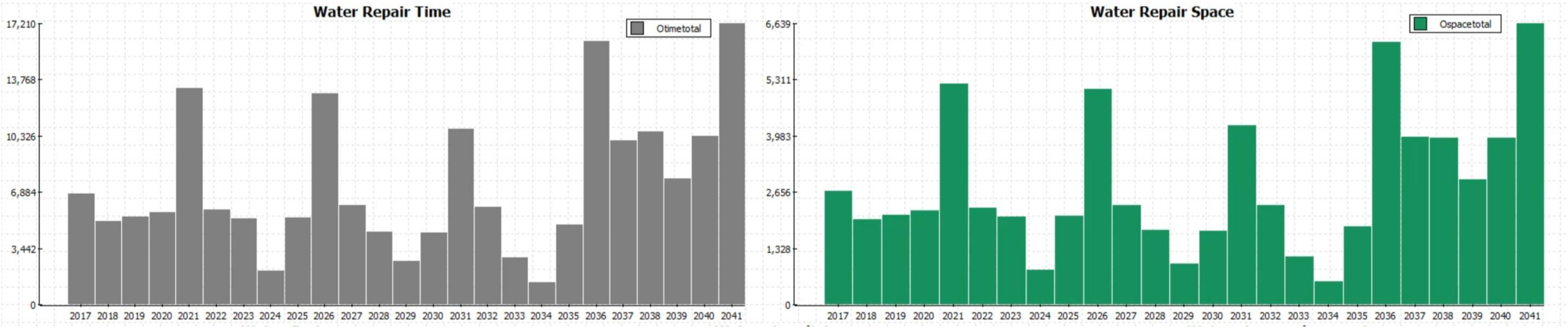
This scenario was carried out on the water network. MOSEK linear optimization engine was used to reach an exact optimal intervention plan that meets the pre-defined contractual KPIs' thresholds across the planning horizon, as highlighted previously in sub-section 5.2.1.1. The objective of the water network conventional optimization was maximizing the improvement deviational variables across the planning horizon as discussed in Equation 3.109. The constraints were meeting the unacceptable performance and demand-capacity ratio thresholds defined earlier in Equations 3.111 and 3.112. The variables were the optimal intervention actions that need to be taken for each corridor at each point of time across the planning horizon as highlighted earlier in Equation 3.108 (i.e. corridor 18 requires a pipe replacement in year 6). The optimization results could be summarized in Table **5-19** and Figure 5.18. The results displayed a total of 303 intervention actions split into 3 for pipelining, 269 for the replacement for the same diameter, and 31 replacements with a bigger diameter. This distribution is because the network was in an excellent condition state and fair resilience preparedness. Thus, undertaking replacement actions for bigger diameter improved the resilience preparedness by 19% dropping from 61% to 42% demand-capacity ratio as displayed in Figure 5.18 (C). The average number of revisits for each corridor was 2 times. The average number of interventions per year was 12 interventions for the 125 corridors, which results in an average disruption ratio of 10%. The fact that the replacement actions are lengthy even extends the public nuisance and results in more repair time as opposed to road repairs. As shown in Figure 5.18 (A), the overall water network was in a very good initial reliability of 87.5%. After running the optimization for 25 years, the reliability improved to 94% because of the undertaken replacement actions. Furthermore, as a result of the improved reliability, the risk index dropped from 12% to 6% as displayed in Figure 5.18 (B). The annual intervention time could be displayed in Figure 5.18 (D). The intervention program resulted in 183,000 repair hours over the 25 years with an average of 138 repair hours per km per year. Similarly, the annual intervention space could be displayed in Figure 5.18 (E). The intervention program resulted in 71,000 m^2 repair space over the 25 years with an average of 5.4 km per year. The annual intervention costs for pipelining and replacement could be displayed in Figure 5.18 (F). The cost breakdown of the pipelining could be displayed in Figure 5.18 (G). Furthermore, the annual replacement costs could be displayed in Figure 5.18 (H). The intervention program resulted in NPW of $13.7 million, equivalent to an EUAC of $702,000, for pipelining and replacing the 53 km of Kindersley's water network. Those costs were broken-down to 17% for pipelining, amounting \$2.3 million over the 25 years planning horizon, and 83% for replacement, amounting \$11.4 million over the 25 years planning horizon. The average annual expenditures were \$13,250 \$/year/km.

Table 5-19: *Scenario 2 - Optimization summary results*

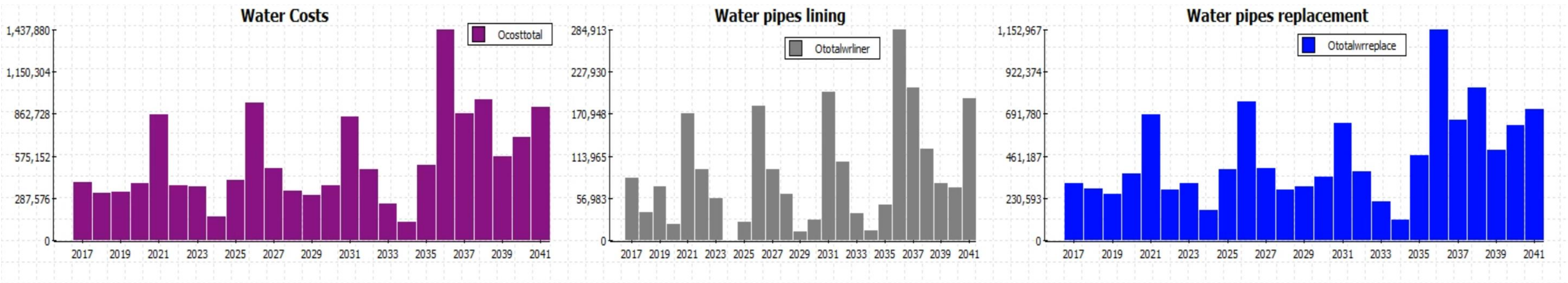
KPI	Water
Time (hours)	182,878
Space (m^2)	71,156
Cost – Equivalent Uniform Annual Cost (EUAC) (\$)	\$702,248
Cost – Net Present Worth (NPW) (\$)	\$13,710,317
Average Condition (%)	74%
Average Risk (%)	26%
Average Resilience (%)	57%
# of intervention actions	303
Time per km per year (hours/km/year)	138
Cost per km per year (\$//km/year)	\$13,249.97
Average repair length per year (km/year)	5.4
Average number of interventions per year	12.12
Ratio of interventions per year - number of annual interventions/number of corridors (%)	10%



A – *Network reliability* **B –** *Network risk* **C-** *Network Resilience Preparedness*



D – *Network repair time* **E –** *Network space*



F – *Water network direct and indirect costs* **G –** *Water pipes' lining costs* **H –** *Water pipes' replacement costs*

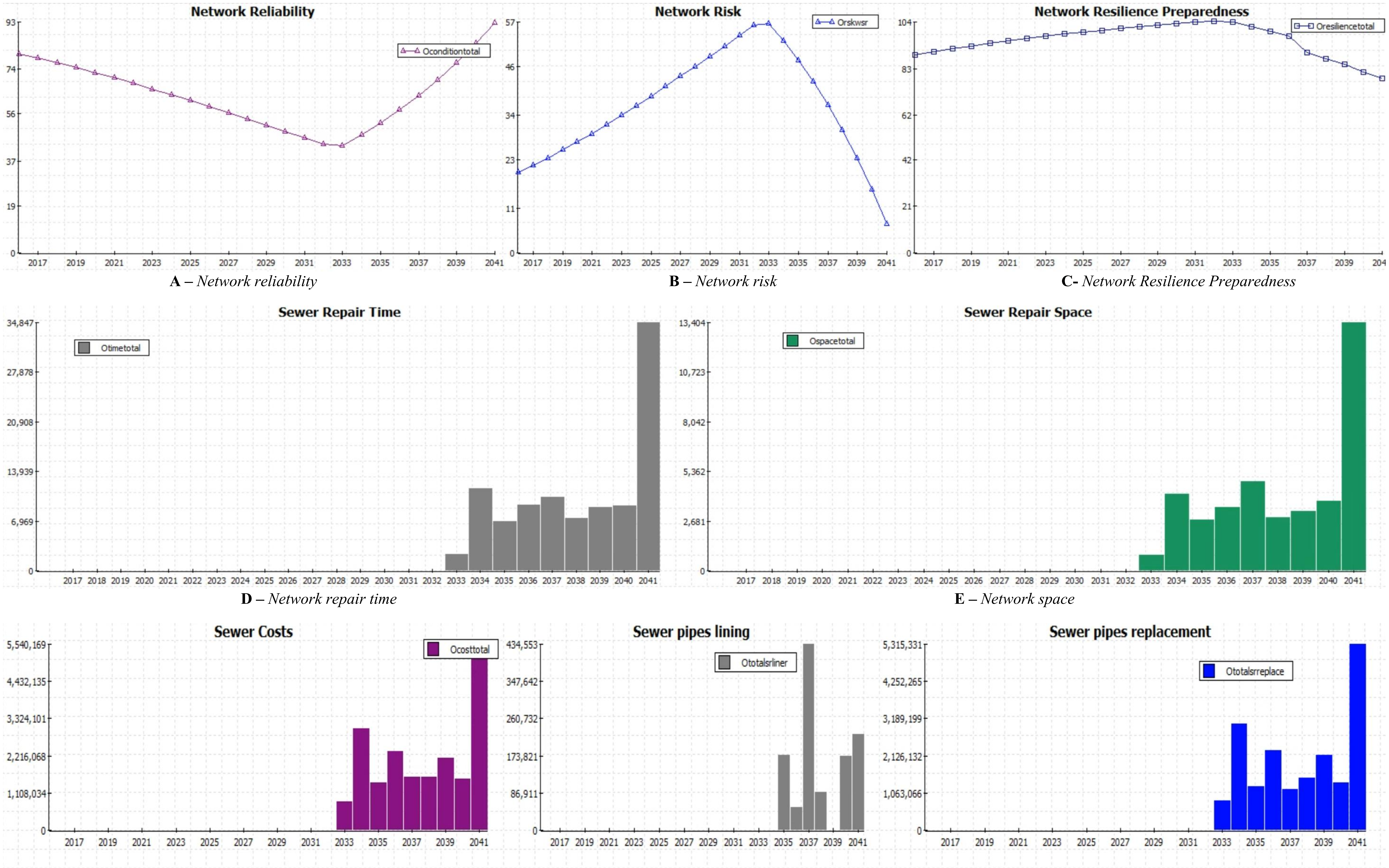
Figure 5.18: *Scenario 2 – MOSEK Optimization results*

C. Scenario 3 (Conventional sewer)

This scenario was carried out on the sewer network. MOSEK linear optimization engine was used to reach an exact optimal intervention plan that meets the pre-defined contractual KPIs' thresholds across the planning horizon, as highlighted previously in sub-section 5.2.1.1. The objective of the sewer network conventional optimization was maximizing the improvement deviational variables across the planning horizon as discussed in Equation 3.109. The constraints were meeting the unacceptable performance and demand-capacity ratio thresholds defined earlier in Equations 3.111 and 3.112. The variables were the optimal intervention actions that need to be taken for each corridor at each point of time across the planning horizon as highlighted earlier in Equation 3.108 (i.e. corridor 16 requires a pipelining in year 6). The optimization results could be summarized in Table **5-20** and Figure **5.19**. The results displayed a total of 197 intervention actions split into 28 for pipelining, 108 for the replacement for the same diameter, and 61 replacements with a bigger diameter. This distribution is because the network was in a very good condition state and poor resilience preparedness. Thus, undertaking replacement actions for bigger diameter improved the resilience preparedness by 11% dropping from 89% to 78% demand-capacity ratio as displayed in Figure **5.19** (C). The average number of revisits for each corridor was 1 time. The average number of interventions per year was 7 interventions for the 125 corridors, which results in an average disruption ratio of 6%. The fact that the replacement actions are lengthy even extends the public nuisance and results in more repair time as opposed to road repairs. As shown in Figure **5.19** (A), the overall sewer network was in a very good initial reliability of 80%. After running the optimization for 25 years, the reliability improved to 93% because of the undertaken replacement actions. Furthermore, as a result of the improved reliability, the risk index dropped from 20% to 7% as displayed in Figure **5.19** (B). The annual intervention time could be displayed in Figure **5.19** (D). The intervention program resulted in 100,000 repair hours over the 25 years with an average of 76 repair hours per km per year. Similarly, the annual intervention space could be displayed in Figure **5.19** (E). The intervention program resulted in 39,200 m^2 repair space over the 25 years with an average of 3 km per year. The annual intervention costs for pipelining and replacement could be displayed in Figure **5.19** (F). The cost breakdown of the pipelining could be displayed in Figure **5.19** (G). Furthermore, the annual replacement costs could be displayed in Figure **5.19** (H). The intervention program resulted in NPW of $20 million, equivalent to an EUAC of $1 million, for pipelining and replacing the 53 km of Kindersley's sewer network. Those costs were broken-down to 6% for pipelining, amounting $1.2 million over the 25 years planning horizon, and 94% for pipe replacement, amounting $18.8 million over the 25 years planning horizon. The average annual expenditures were $19,350 $/year/km.

Table 5-20: *Scenario 3 - Optimization summary results*

KPI	Sewer
Time (hours)	100,481
Space (m^2)	39,213
Cost – Equivalent Uniform Annual Cost (EUAC) ($)	$1,025,412
Cost – Net Present Worth (NPW) ($)	$20,019,589
Average Condition (%)	64%
Average Risk (%)	36%
Average Resilience (%)	96%
# of intervention actions	197
Time per km per year (hours/km/year)	76
Cost per km per year ($//km/year)	$19,347.40
Average repair length per year (km/year)	3.0
Average number of interventions per year	7.88
Ratio of interventions per year - number of annual interventions/number of corridors (%)	6%



A – *Network reliability*

B – *Network risk*

C- *Network Resilience Preparedness*

D – *Network repair time*

E – *Network space*

F – *Sewer network direct and indirect costs*

G – *Sewer pipes' lining costs*

H – *Sewer pipes' replacement costs*

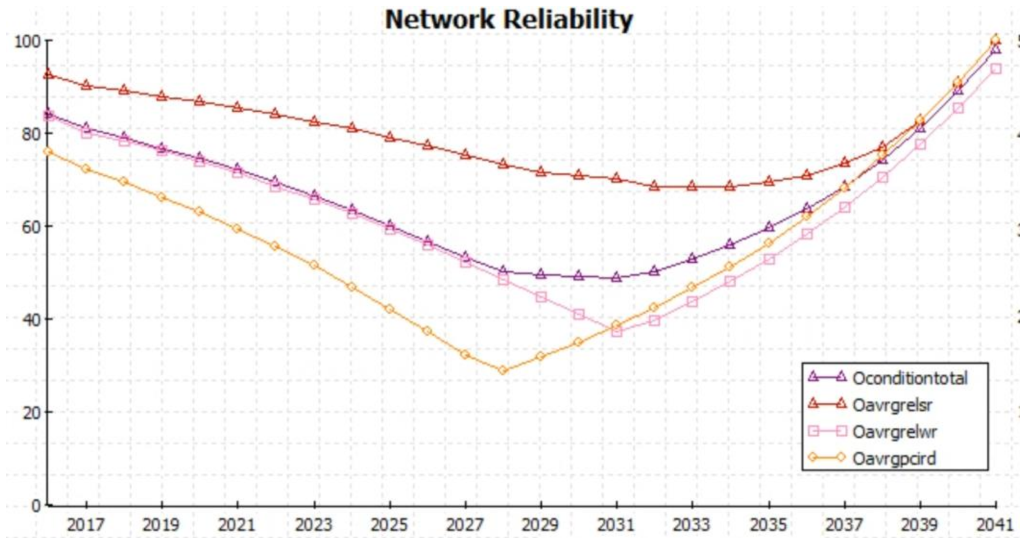
Figure 5.19: *Scenario 3 – MOSEK Optimization results*

D. Scenario 4 (Combined conventional – roads + water + sewer)

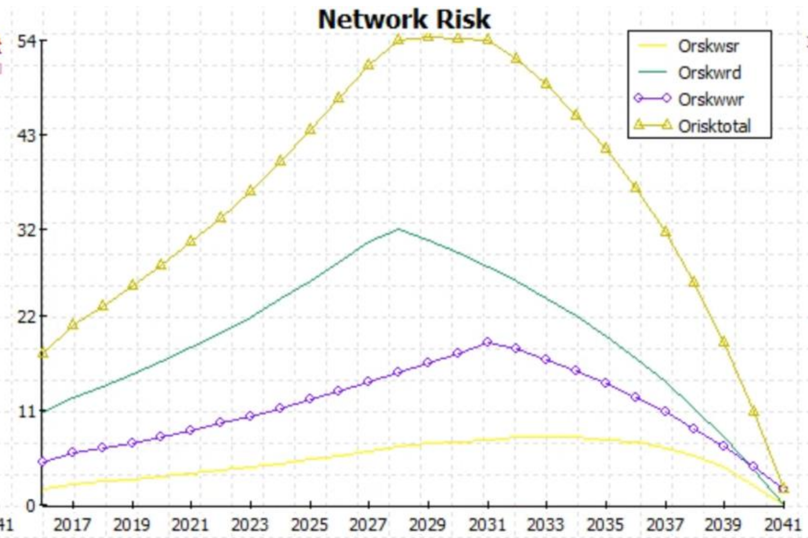
This scenario was carried out on the combined conventional roads, water, and sewer networks. MOSEK linear optimization engine was used to reach an exact optimal intervention plan that meets the pre-defined contractual KPIs' thresholds across the planning horizon, as highlighted previously in sub-section 5.2.1.1. The objective of the combined conventional optimization was maximizing the improvement deviational variables across the planning horizon as discussed in Equation 3.109. The constraints were meeting the unacceptable performance and demand-capacity ratio thresholds defined earlier in Equations 3.111 and 3.112. The variables were the optimal intervention actions that need to be taken for each system within each corridor at every single point of time across the planning horizon as highlighted earlier in Equation 3.108. The optimization results could be summarized in Table **5-21** and Figure **5.20**. The results displayed a total of 560 intervention actions split into 183 for roads, 144 for sewer (67 replacement with bigger diameter), and 233 for water (103 replacements with bigger diameter). This distribution is because the water and sewer networks were in a very good condition state and poor resilience preparedness. Thus, undertaking replacement actions for bigger diameter improved the resilience preparedness by 14% dropping from 75% to 61% demand-capacity ratio as displayed in Figure **5.20** (C). The average number of revisits for each corridor was 4 times, which represents two road activities and the other two activities are for the water and sewer pipes. The average number of interventions per year was 22 interventions for the 125 corridors, which results in an average disruption ratio of 18%. The fact that there is no coordination among the three spatially located assets increased the public nuisance and results in more repair time as opposed to coordinated interventions. As shown in Figure **5.20** (A), the overall network was in a very good initial reliability of 84%. After running the optimization for 25 years, the reliability improved to 98% because of the undertaken replacement actions. Furthermore, as a result of the improved reliability, the risk index dropped from 17% to 2% as displayed in Figure **5.20** (B). The annual intervention time could be displayed in Figure **5.20** (D). The intervention program resulted in 2.7 million repair hours over the 25 years with an average of 2,000 repair hours per km per year. Similarly, the annual intervention space could be displayed in Figure **5.20** (E). The intervention program resulted in 397,000 m^2 repair space over the 25 years with an average of 5.2 km per year. The annual intervention costs for roads repair, rehabilitation, reconstruction, as well as the pipelining and replacement could be displayed in Figure **5.20** (F). The cost breakdown of the road repair, rehabilitation, and pipelining could be displayed in Figure **5.20** (G). Furthermore, the annual pipe replacement and road reconstruction costs could be displayed in Figure **5.20** (H). The intervention program resulted in NPW of $57 million, equivalent to an EUAC of $3 million, for undertaking the conventional intervention actions for the 53 km of Kindersley's road, water, and sewer networks. Those costs were broken-down to 22% for roads repair and rehabilitation as well as pipelining, amounting $12.5 million over the 25 years planning horizon, and 78% for pipe replacement and road reconstruction, amounting $44.5 million over the 25 years planning horizon. The average annual expenditures were $55,000 $/year/km.

Table 5-21: *Conventional (Scenario 4) - Optimization summary results*

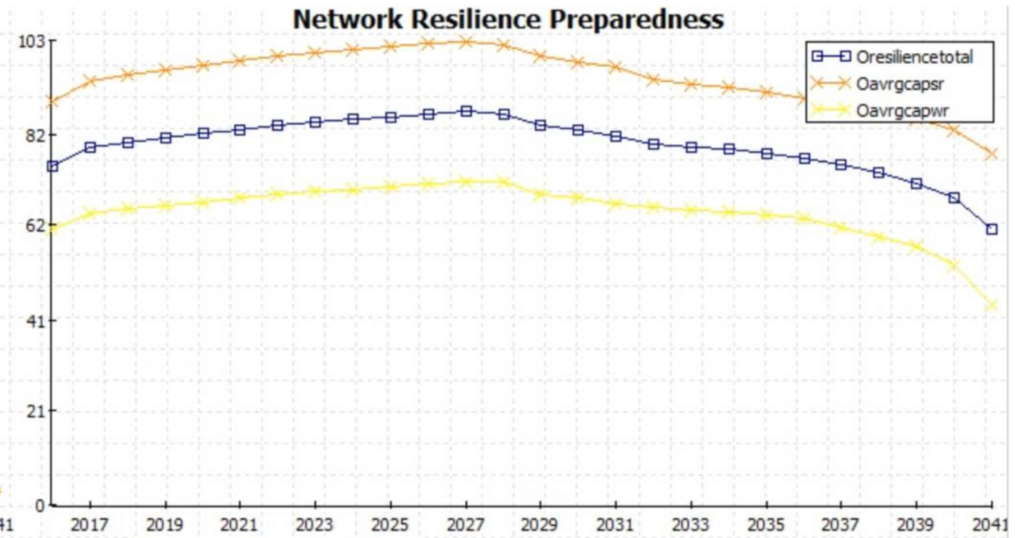
KPI	Combined Conventional (Total)	Roads	Water	Sewer
Time (hours)	2,673,608	2,052,245	577,970	43,392
Space (m^2)	397,069	157,276	222,038	17,757
Cost – Equivalent Uniform Annual Cost (EUAC) ($)	$2,918,743	$591,343	$1,904,109	$423,290
Cost – Net Present Worth (NPW) ($)	$56,983,949	$11,545,060	$37,174,798	$8,264,092
Average Condition (%)	66%	57%	63%	79%
Average Risk (%)	36%	19%	11%	5%
Average Resilience (%)	80%	N/A	65%	95%
# of intervention actions	560	183	233	144
Time per km per year (hours/km/year)	2,018	1,549	436	33
Cost per km per year ($//km/year)	$55,070.62	$11,157.42	$35,926.59	$7,986.61
Average repair length per year (km/year)	5.2	2.2	1.7	1.3
Average number of interventions per year	22.4	7.32	9.32	5.76
Ratio of interventions per year - number of annual interventions/number of corridors (%)	18%	6%	7%	5%



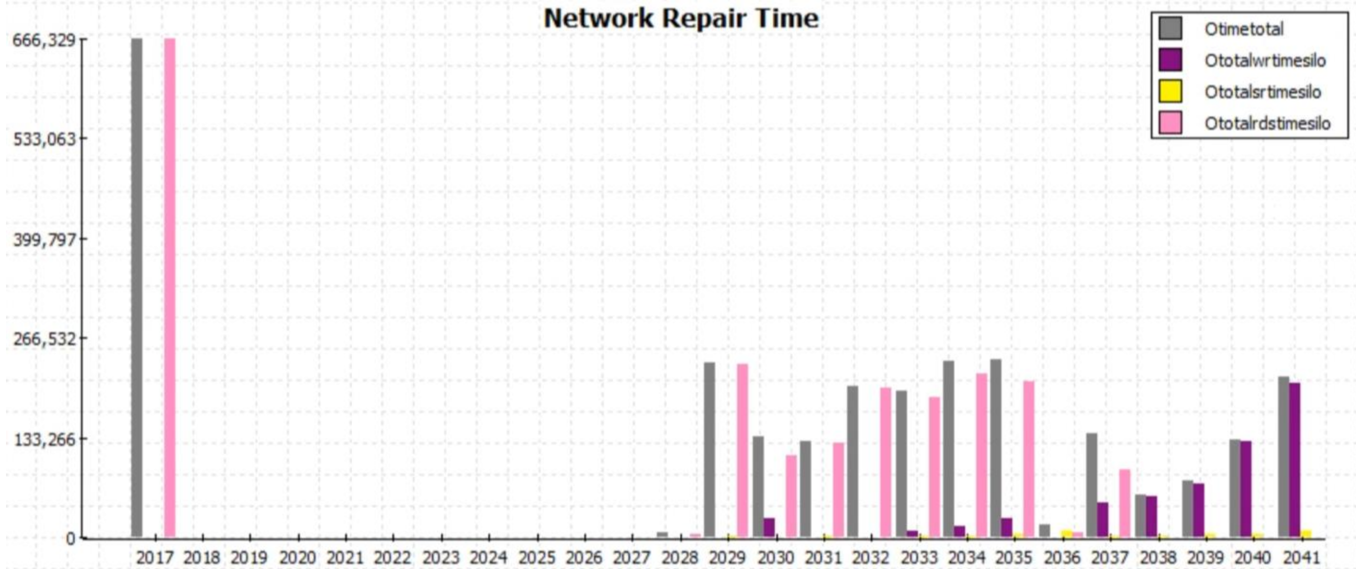
A – *Network reliability*



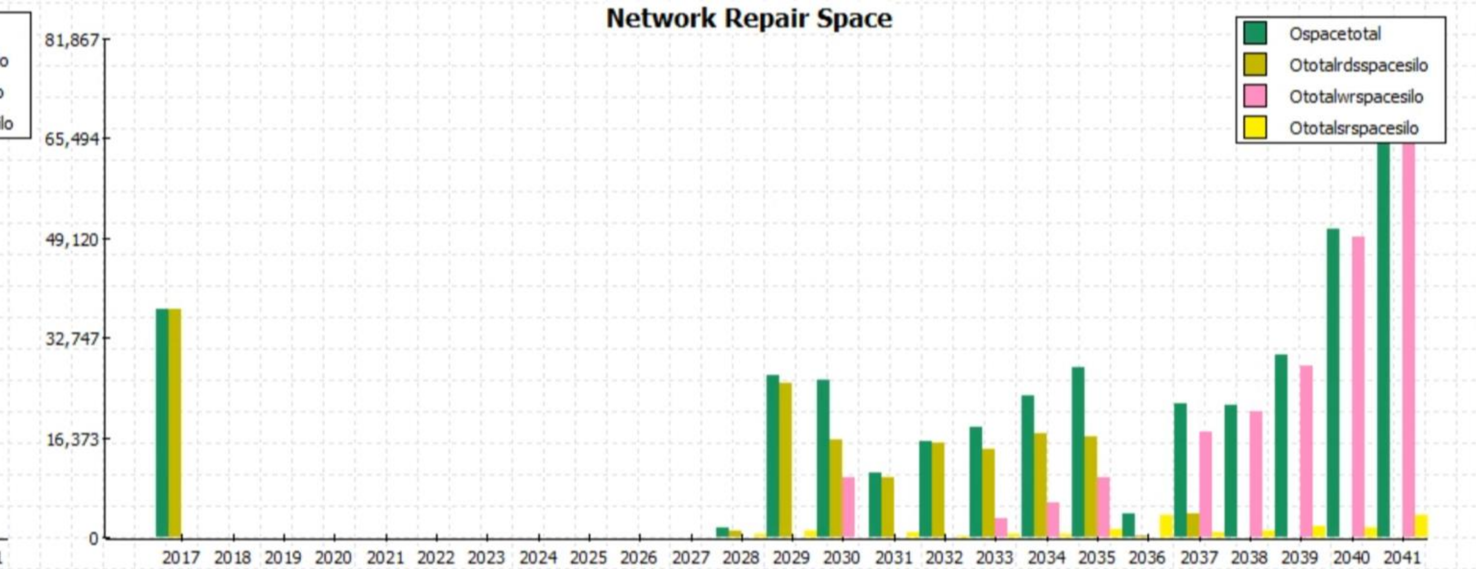
B – *Network risk*



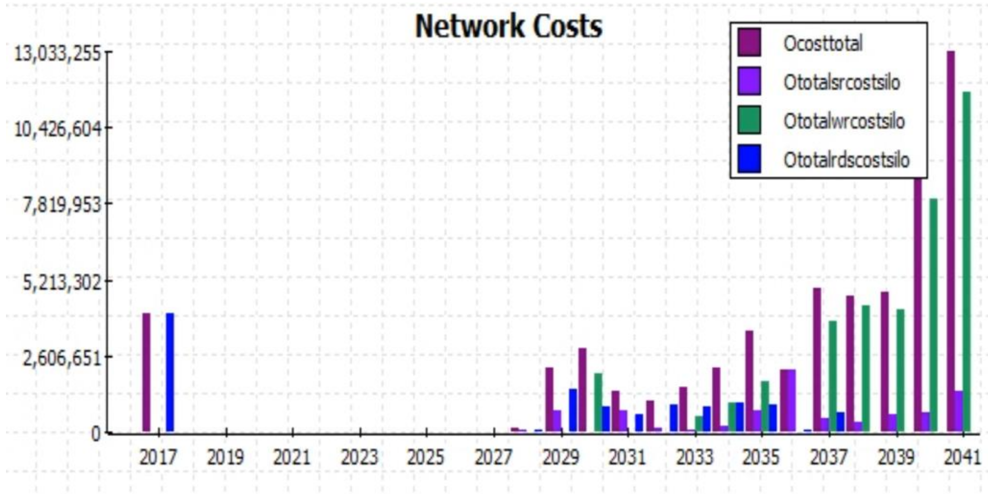
C- *Network Resilience Preparedness*



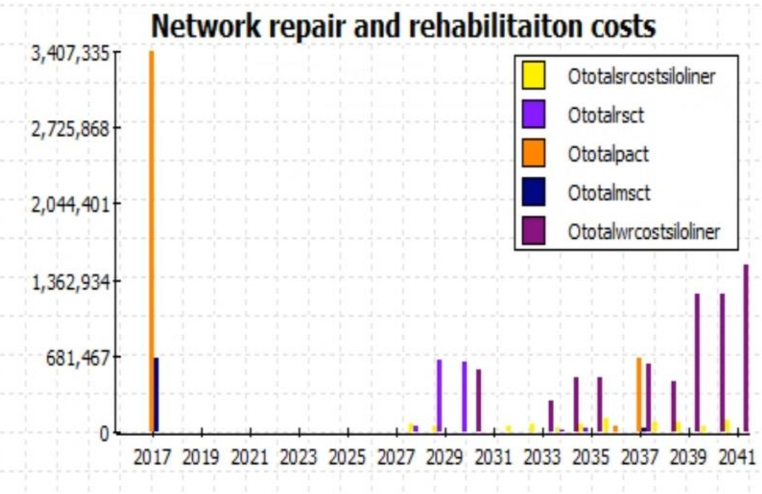
D – *Network repair time*



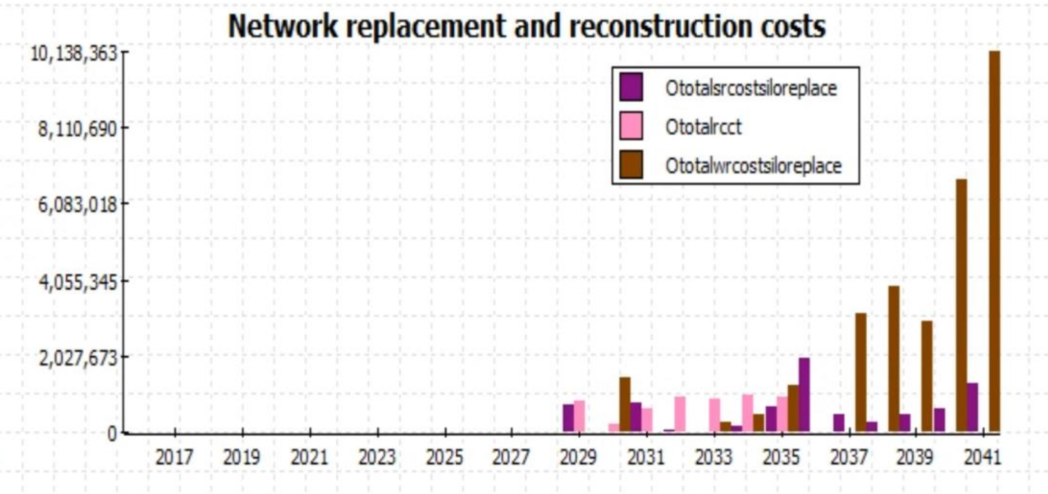
E – *Network space*



F –*Conventional network direct and indirect costs*



G – *Conventional repair and rehabilitation costs*



H – *Conventional replacement and reconstruction costs*

Figure 5.20: *Conventional Summary (Scenario 4) – MOSEK Optimization results*

5.3.1.2 *Partially-Coordinated Optimization Results*

The partially-coordinated optimization aims at reaching an exact optimal intervention plan for the network on the basis of partially coordinating the interventions of two out of the three networks together and undertaking conventional interventions for the third system. Similarly, the study was carried out across 25 years planning horizon. Scenario 5 through 7 were conducted for the partially-coordinated roads and water and conventional sewer; partially-coordinated roads and sewer with conventional water; and partially-coordinated water and sewer with conventional roads respectively. Finally, the partially-coordinated optimization results were compared with the optimization results of the combined conventional (scenario 4) and improvements were computed accordingly as will be discussed in the upcoming sub-sections.

A. <u>Scenario 5 (Partially-coordinated – roads and sewer + conventional water)</u>

This scenario was carried out on the partially-coordinated roads and sewer networks along with the conventional water network. MOSEK linear optimization engine was used to reach an exact optimal intervention plan that meets the pre-defined contractual KPIs' thresholds across the planning horizon, as highlighted previously in sub-section 5.2.1.1. The objective of the partially-coordinated optimization was maximizing the improvement deviational variables across the planning horizon as discussed in Equation 3.109. The constraints were meeting the unacceptable performance and demand-capacity ratio thresholds defined earlier in Equations 3.111 and 3.112. The variables were the optimal intervention actions that need to be taken for each system within each corridor at every single point of time across the planning horizon as highlighted earlier in Equation 3.108. The optimization results could be summarized in Table **5-22** and Figure **5.21**. The results displayed a total of 271 intervention actions split into 37 for conventional road actions, 112 for water (13 replacement with bigger diameter), and 122 for partially-coordinated road and sewer (112 replacements with bigger diameter). This distribution is because the water and sewer networks were in a very good condition state and poor resilience preparedness. Thus, undertaking replacement actions for bigger diameter improved the resilience preparedness by 33% dropping from 75% to 37% demand-capacity ratio as displayed in Figure **5.21** (C). The average number of revisits for each corridor was 2 times, which shows the potential savings compared to the combined conventional scenario. The average number of interventions per year was 10 interventions for the 125 corridors, which results in an average disruption ratio of 9%. As shown in Figure **5.21** (A), the overall network was in a very good initial reliability of 84%. After running the optimization for 25 years, the reliability improved to 98% because of the undertaken replacement actions. Furthermore, as a result of the improved reliability, the risk index dropped from 20% to 2% as displayed in Figure **5.21** (B). The annual intervention time could be displayed in Figure **5.21** (D). The intervention program resulted in 1 million repair hours over the 25 years with an average of 825 repair hours per km per year, which reveals an NCR of 59% as opposed to the combined conventional scenario. Similarly, the annual intervention space could be displayed in Figure **5.21** (E). The intervention program resulted in 282,000 m^2 repair space over the 25 years with an average of 3.4 km per year. The annual intervention costs for conventional roads and water as well as the partially-coordinated road and sewer could be displayed in Figure **5.21** (F). The cost breakdown of the partially-coordinated intervention actions could be displayed in Figure **5.21** (G). Furthermore, the conventional road and water costs could be displayed in Figure **5.21** (H). The intervention program resulted in NPW of $69 million, equivalent to an EUAC of $3.5 million, for undertaking the conventional and partially-combined roads and sewer intervention actions for the 53 km of Kindersley's road, water, and sewer networks. Those costs were broken-down to 46% for partially-coordinated intervention actions, amounting $32 million over the 25 years planning horizon, and 54% for conventional roads and water, amounting $37 million over the 25 years planning horizon. The average annual expenditures were $67,000 $/year/km.

As discussed earlier in the methodology, the coordination scenarios are compared with the combined conventional one to compute the potential savings in terms of the pre-defined multi-dimensional performance assessment indicators. Accordingly, the partially-coordinated roads and sewer scenario was compared with the combined conventional scenario and the results are outlined in Table **5-23** and Table **5-24**. The results displayed huge temporal and spatio-temporal savings represented through a 59% NCR and 29% STIF. However, this coordination scenario was not cost-effective as it revealed a LIF of -22%, which represents extra costs as opposed to the conventional scenario. Furthermore, the results displayed a slightly improved condition, resilience preparedness, and risk. Those savings were represented through a 1% CIF, 6% RPIF, and 5% RIF reflecting minor improvements in terms of condition, resilience preparedness, and risk. For the efficiency and effectiveness, the results displayed an IEF of 52% and IFF of 2%, which reflects less public disruptions (i.e. less disruption time, a fewer number of interventions) with longer corridor/asset operating times. Through combining the above-mentioned coordination savings, the partially-coordinated roads and sewer scenario revealed an overall improvement of 9% as opposed to the combined conventional one.

Table 5-22: *Scenario 5 - Optimization summary results*

KPI	Combined Network (Total)	Roads and Sewer	Water	Roads conventional
Time (hours)	1,093,561	91,449	494,194	507,914
Space (m^2)	282,758	19,283	190,943	72,530
Cost – Equivalent Uniform Annual Cost (EUAC) ($)	$3,569,007	$1,653,598	$1,717,999	$197,409
Cost – Net Present Worth (NPW) ($)	$69,679,348	$32,283,956	$33,541,282	$3,854,110
# of intervention actions	271	122	112	37
Time per km per year (hours/km/year)	825	69	373	383
Cost per km per year ($//km/year)	$67,339.75	$31,199.97	$32,415.08	$3,724.70
Average repair length per year (km/year)	3.4	1.5	1.4	0.5
Average number of interventions per year	10.84	4.88	4.48	1.48
Ratio of interventions per year - number of annual interventions/number of corridors (%)	9%	4%	4%	1%
KPI	**Combined Network (Total)**	**Roads**	**Water**	**Sewer**
Average Condition (%)	67%	61%	74%	66%
Average Risk (%)	34%	18%	8%	18%
Average Resilience (%)	75%	N/A	64%	86%

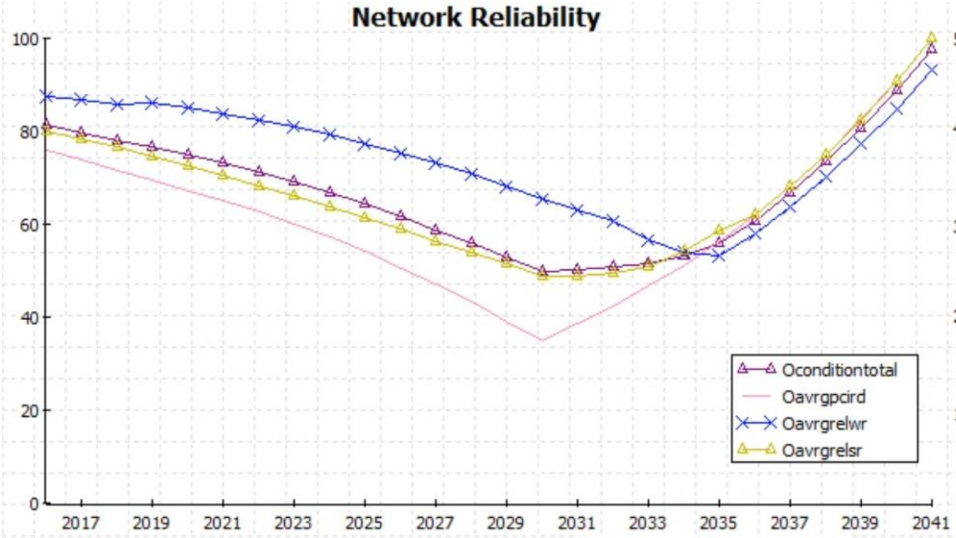
Table 5-23: *Scenario 5 – KPIs' comparison with combined conventional scenario*

KPI	Scenario 4 - Combined Conventional (Baseline)	Scenario 5 - Roads and sewer	Scenario 5 - Roads and sewer (Difference)
Time (hours)	2,673,608	1,093,561	59%
Space (m^2)	397,069	282,758	29%

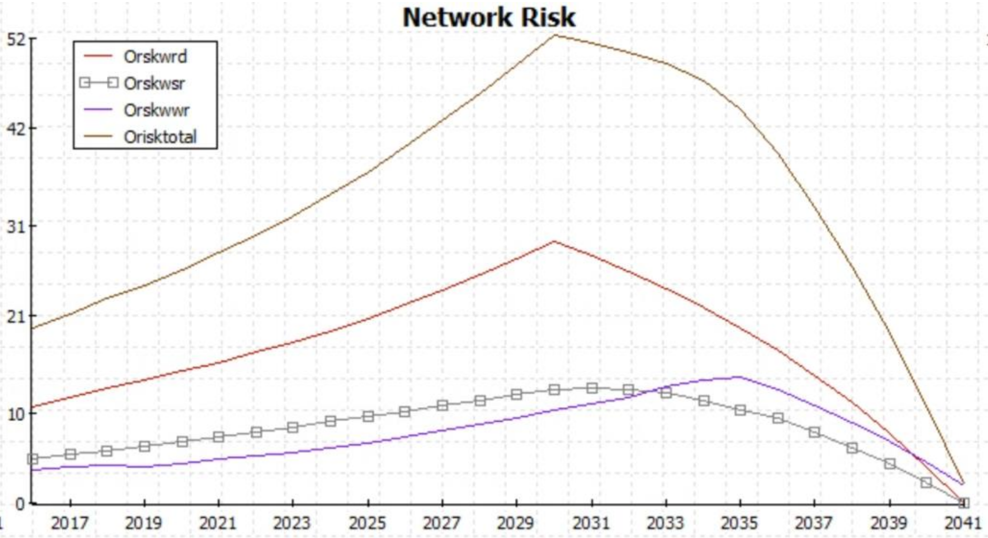
Cost – Equivalent Uniform Annual Cost (EUAC) ($)	$2,918,743	$3,569,007	-22%
Cost – Net Present Worth (NPW) ($)	$56,983,949	$69,679,348	-22%
Average Condition (%)	66%	67%	1%
Average Risk (%)	36%	34%	5%
Average Resilience (%)	80%	75%	6%
# of intervention actions	560	271	52%
Time per km per year (hours/km/year)	2,018	825	59%
Cost per km per year ($//km/year)	$55,070.62	$67,339.75	-22%
Average repair length per year (km/year)	5.2	3.4	34%
Average number of interventions per year	22.4	10.84	52%
Ratio of interventions per year - number of annual interventions/number of corridors (%)	18%	9%	52%

Table 5-24: *Scenario 5 –Performance indicators' (Improvement deviational variables)*

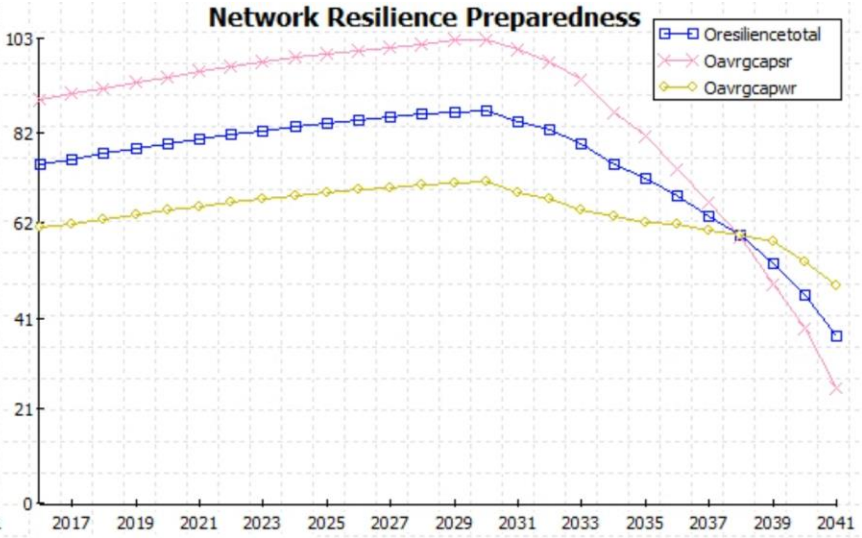
Performance Indicator	KPI	Weights of importance (%)	Scenario 5 - Roads and sewer
Time	NCR	10%	59%
Space	STIF	10%	29%
Cost	LIF	20%	-22%
Efficiency	IEF	5%	52%
Effectiveness	IFF	5%	2%
Condition	CIF	20%	1%
Resilience Preparedness	RPIF	10%	6%
Risk	RIF	20%	5%
Overall Improvement (%)			***9%***



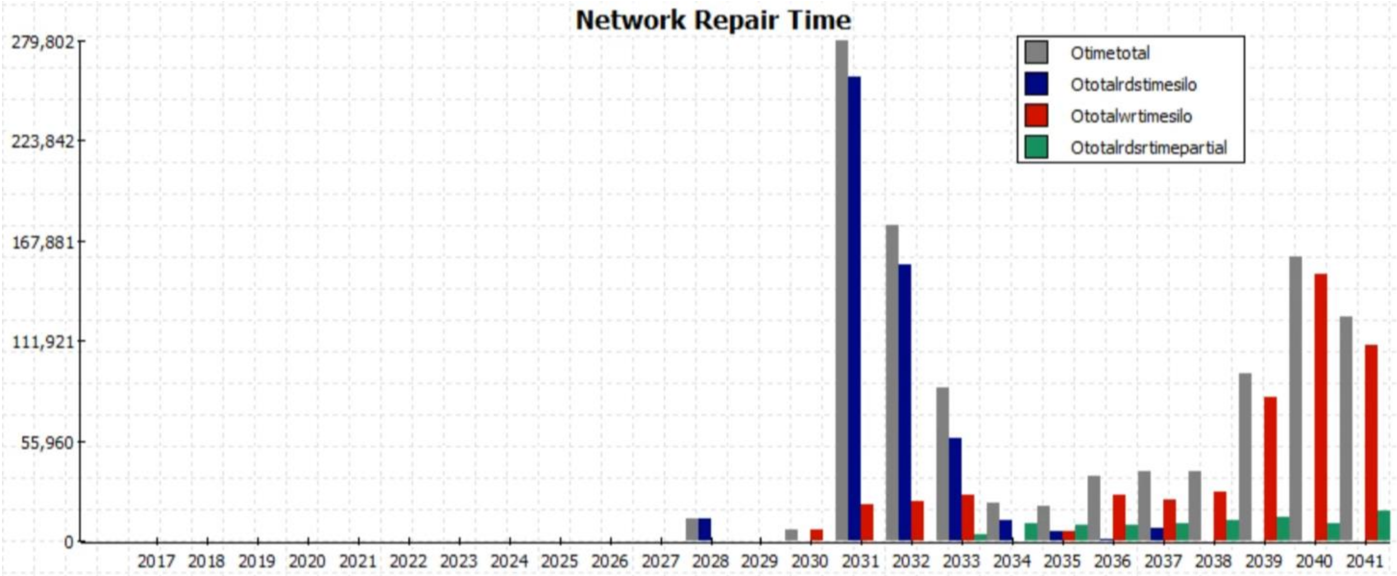
A – *Network reliability*



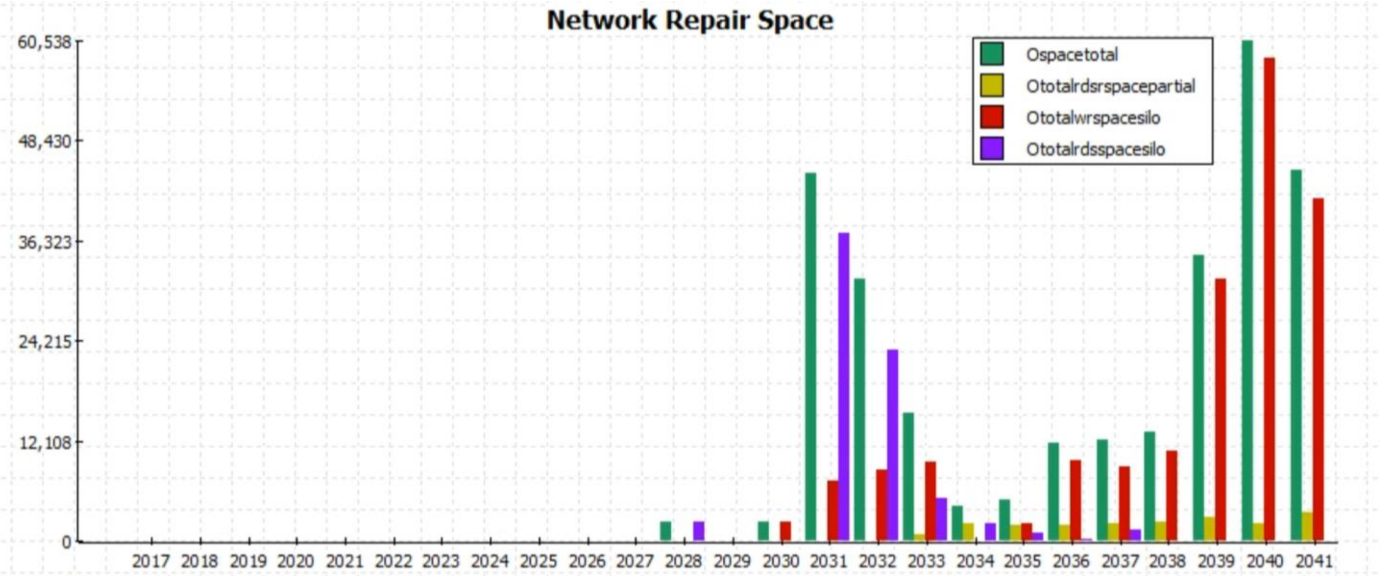
B – *Network risk*



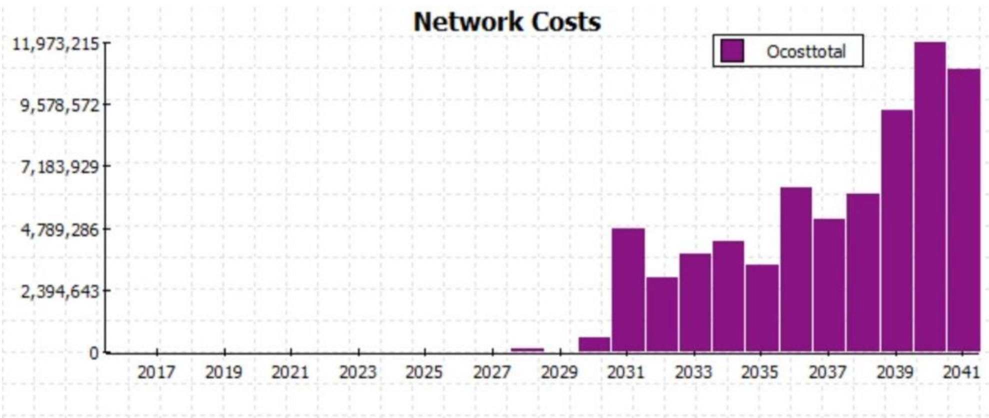
C- *Network Resilience Preparedness*



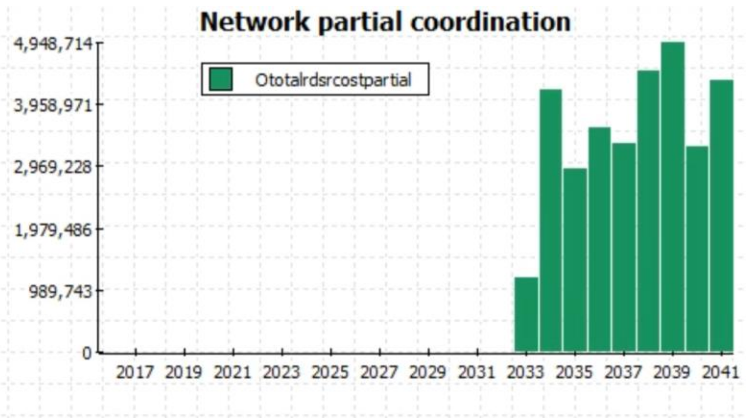
D – *Network repair time*



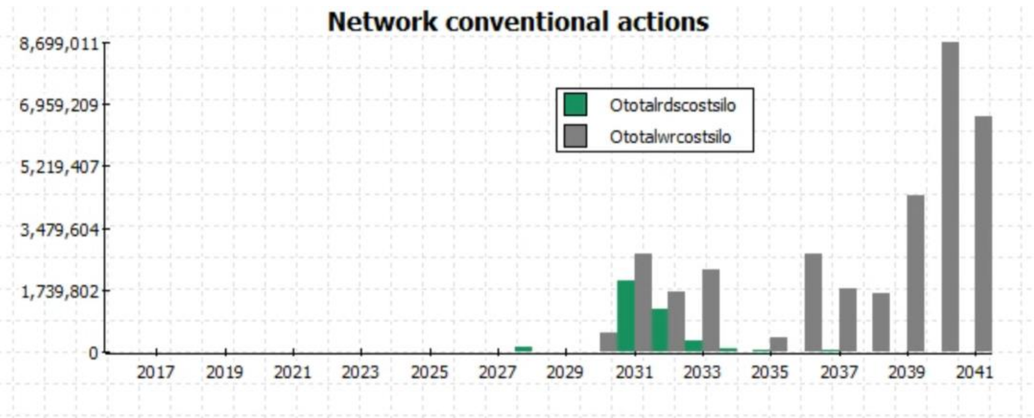
E – *Network space*



F – *Network direct and indirect costs*



G – *Network partial coordination costs*



H – *Network conventional costs*

Figure 5.21: *Scenario 5 – MOSEK Optimization results*

B. Scenario 6 (Partially-coordinated – roads and water + conventional sewer)

This scenario was carried out on the partially-coordinated roads and water networks along with the conventional sewer network. MOSEK linear optimization engine was used to reach an exact optimal intervention plan that meets the pre-defined contractual KPIs' thresholds across the planning horizon, as highlighted previously in sub-section 5.2.1.1. The objective of the partially-coordinated optimization was maximizing the improvement deviational variables across the planning horizon as discussed in Equation 3.109. The constraints were meeting the unacceptable performance and demand-capacity ratio thresholds defined earlier in Equations 3.111 and 3.112. The variables were the optimal intervention actions that need to be taken for each system within each corridor at every single point of time across the planning horizon as highlighted earlier in Equation 3.108. The optimization results could be summarized in Table **5-25** and Figure **5.22**. The results displayed a total of 316 intervention actions split into 82 for conventional road actions, 168 for sewer (42 replacement with bigger diameter), and 66 for partially-coordinated road and water (18 replacements with bigger diameter). This distribution is because the water and sewer networks were in a very good condition state and poor resilience preparedness. Thus, undertaking replacement actions for bigger diameter improved the resilience preparedness by 11% dropping from 75% to 64% demand-capacity ratio as displayed in Figure **5.22** (C). The average number of revisits for each corridor was 2 times, which shows the potential savings compared to the combined conventional scenario. The average number of interventions per year was 12 interventions for the 125 corridors, which results in an average disruption ratio of 10%. As shown in Figure **5.22** (A), the overall network was in a very good initial reliability of 84%. After running the optimization for 25 years, the reliability improved to 95% because of the undertaken replacement actions. Furthermore, as a result of the improved reliability, the risk index dropped from 20% to 4% as displayed in Figure **5.22** (B). The annual intervention time could be displayed in Figure **5.22** (D). The intervention program resulted in 1.6 million repair hours over the 25 years with an average of 1,200 repair hours per km per year, which reveals an NCR of 40% as opposed to the combined conventional scenario. Similarly, the annual intervention space could be displayed in Figure **5.22** (E). The intervention program resulted in 195,000 m^2 repair space over the 25 years with an average of 3.4 km per year. The annual intervention costs for conventional roads and sewer as well as the partially-coordinated road and water could be displayed in Figure **5.22** (F). The cost breakdown of the partially-coordinated intervention actions could be displayed in Figure **5.22** (G). Furthermore, the conventional road and sewer costs could be displayed in Figure **5.22** (H). The intervention program resulted in NPW of $28 million, equivalent to an EUAC of $1.4 million, for undertaking the conventional and partially-combined roads and water intervention actions for the 53 km of Kindersley's road, water, and sewer networks. Those costs were broken-down to 20% for partially-coordinated intervention actions, amounting $5.7 million over the 25 years planning horizon, and 80% for conventional roads and sewer, amounting $22.3 million over the 25 years planning horizon. The average annual expenditures were $27,000 $/year/km.

As discussed earlier in the methodology, the coordination scenarios are compared with the combined conventional one to compute the potential savings in terms of the pre-defined multi-dimensional performance assessment indicators. Accordingly, the partially-coordinated roads and water scenario was compared with the combined conventional scenario and the results are outlined in Table **5-26** and Table **5-27**. The results displayed huge temporal, spatio-temporal, and cost savings represented through a 40% NCR, 51% STIF, and 51% LIF. However, this coordination scenario displayed no improvement in terms of condition (CIF=0) and resilience preparedness (RPIF=0) as it revealed similar results compared to the combined conventional one. Furthermore, the results displayed a slight improvement in the risk represented through a 4% RIF. For the efficiency and effectiveness, the results displayed an IEF of 44% and IFF of 5%, which reflects fewer public disruptions (i.e. less disruption time, a fewer number of interventions) with longer corridor/asset operating times. Through combining the above-mentioned coordination savings, the partially-coordinated roads and water scenario revealed an overall improvement of 22% as opposed to the combined conventional one.

Table 5-25: *Scenario 6 - Optimization summary results*

KPI	Combined Network (Total)	Roads and Water	Sewer	Roads conventional
Time (hours)	1,614,876	42,122	74,356	1,498,398
Space (m^2)	195,432	12,610	28,965	153,858
Cost – Equivalent Uniform Annual Cost (EUAC) ($)	$1,436,639	$295,928	$699,736	$440,975
Cost – Net Present Worth (NPW) ($)	$28,048,165	$5,777,528	$13,661,271	$8,609,364

KPI	Combined Network (Total)	Roads and Water	Sewer	Roads conventional
# of intervention actions	316	5	229	82
Time per km per year (hours/km/year)	1,219	32	56	1,131
Cost per km per year ($//km/year)	$27,106.40	$5,583.54	$13,202.57	$8,320.29
Average repair length per year (km/year)	3.4	0.1	2.2	1.2
Average number of interventions per year	12.64	0.2	9.16	3.28
Ratio of interventions per year - number of annual interventions/number of corridors (%)	10%	0%	7%	3%
KPI	**Combined Network (Total)**	**Roads**	**Water**	**Sewer**
Average Condition (%)	67%	61%	74%	65%
Average Risk (%)	34%	18%	8%	9%
Average Resilience (%)	80%	N/A	65%	95%

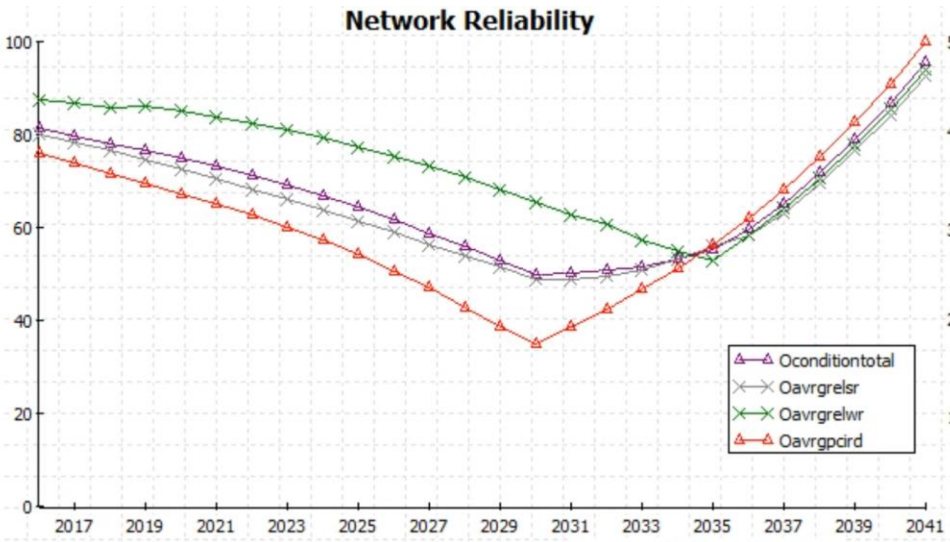
Table 5-26: *Scenario 6 – KPIs' comparison with combined conventional scenario*

KPI	Scenario 4 - Combined Conventional (Baseline)	Scenario 6 - Roads and sewer	Scenario 6 - Roads and sewer (Difference)
Time (hours)	2,673,608	1,614,876	40%
Space (m^2)	397,069	195,432	51%
Cost – Equivalent Uniform Annual Cost (EUAC) ($)	$2,918,743	$1,436,639	51%
Cost – Net Present Worth (NPW) ($)	$56,983,949	$28,048,165	51%
Average Condition (%)	66%	67%	0%
Average Risk (%)	36%	34%	4%
Average Resilience (%)	80%	80%	0%
# of intervention actions	560	316	44%
Time per km per year (hours/km/year)	2,018	1,219	40%
Cost per km per year ($//km/year)	$55,070.62	$27,106.40	51%

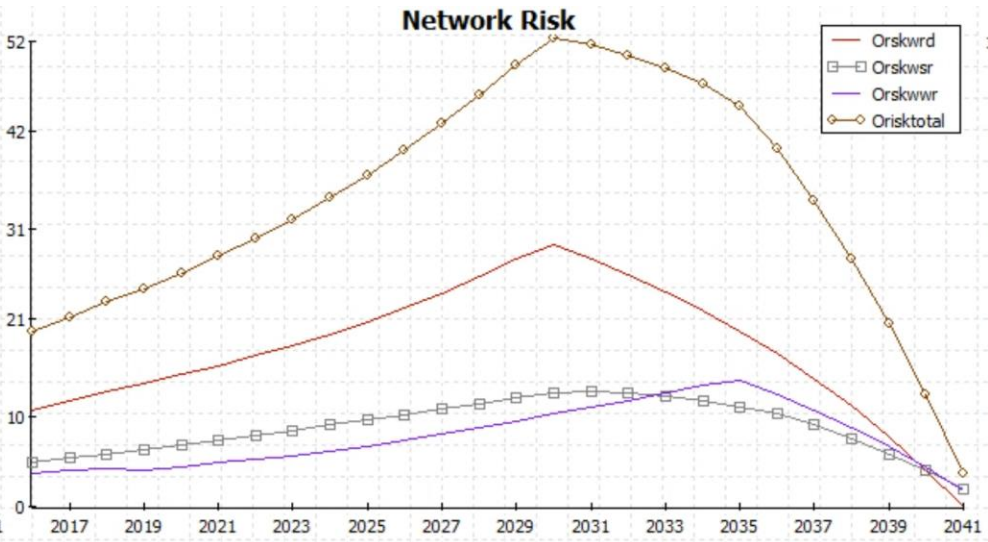
KPI	Scenario 4 - Combined Conventional (Baseline)	Scenario 6 - Roads and sewer	Scenario 6 - Roads and sewer (Difference)
Average repair length per year (km/year)	5.2	3.4	34%
Average number of interventions per year	22.4	12.64	44%
Ratio of interventions per year - number of annual interventions/number of corridors (%)	18%	10%	44%

Table 5-27: *Scenario 6 –Performance indicators' (Improvement deviational variables)*

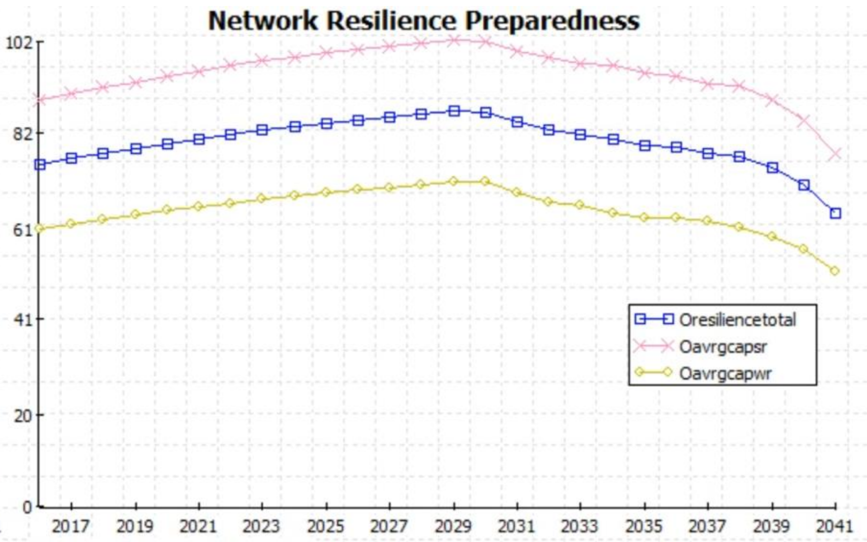
Performance Indicator	KPI	Weights of importance (%)	Scenario 6 - Roads and sewer
Time	NCR	10%	40%
Space	STIF	10%	51%
Cost	LIF	20%	51%
Efficiency	IEF	5%	44%
Effectiveness	IFF	5%	5%
Condition	CIF	20%	0%
Resilience Preparedness	RPIF	10%	0%
Risk	RIF	20%	4%
Overall Improvement (%)			***22%***



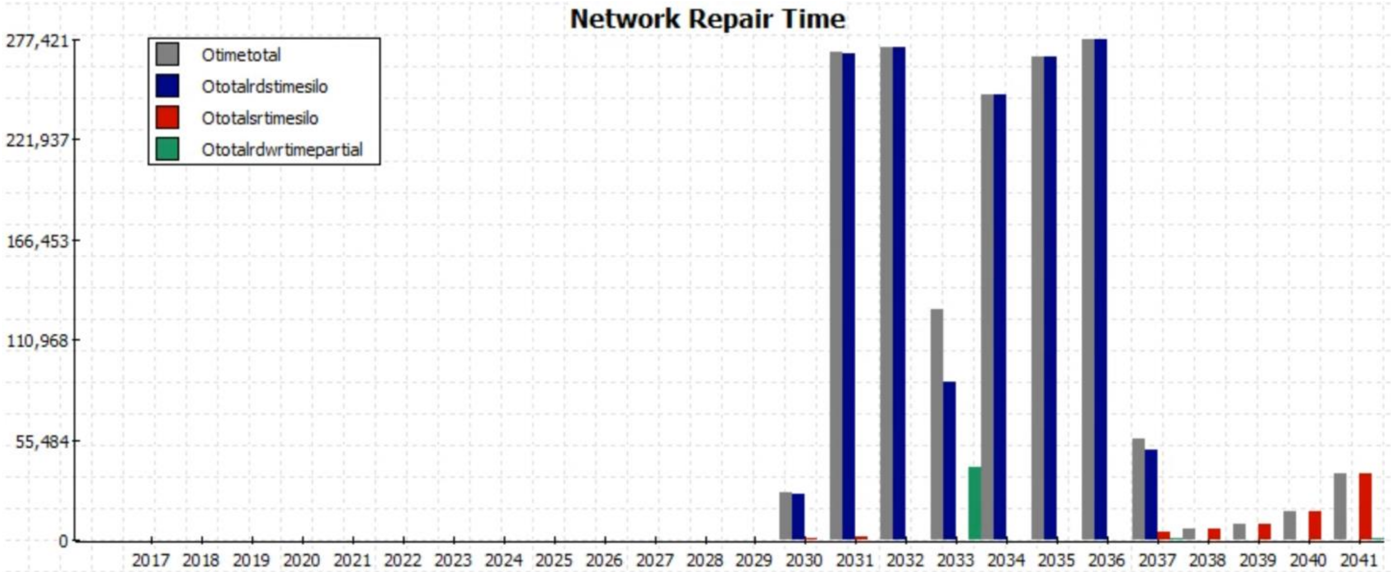
A – *Network reliability*



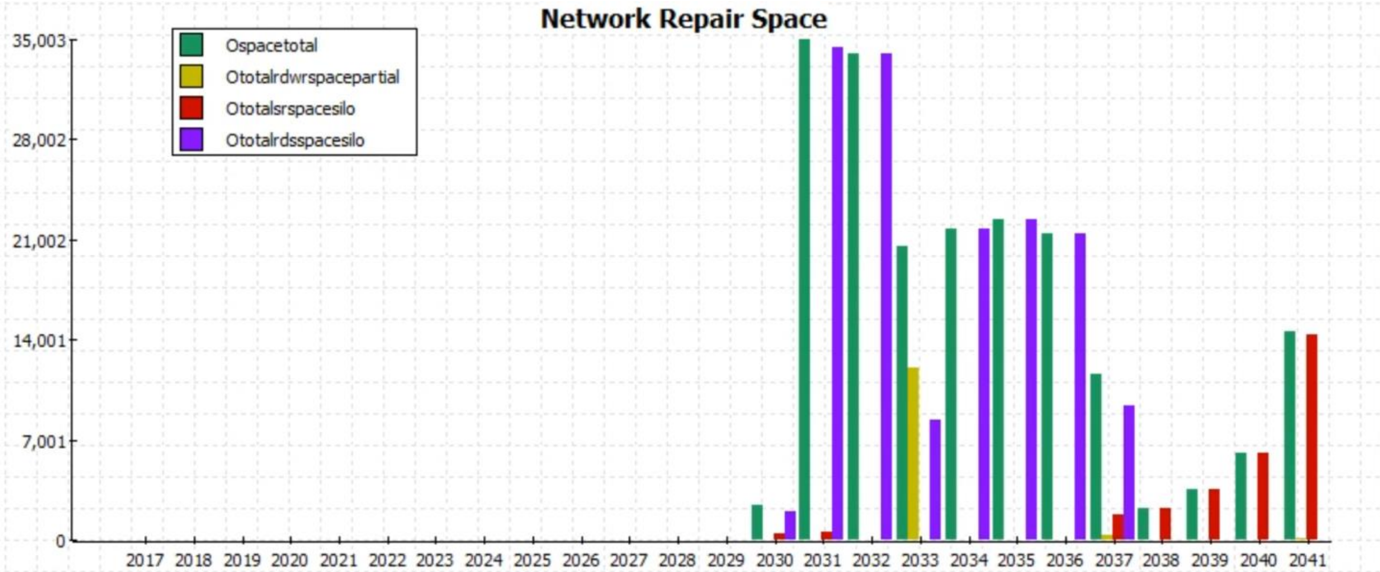
B – *Network risk*



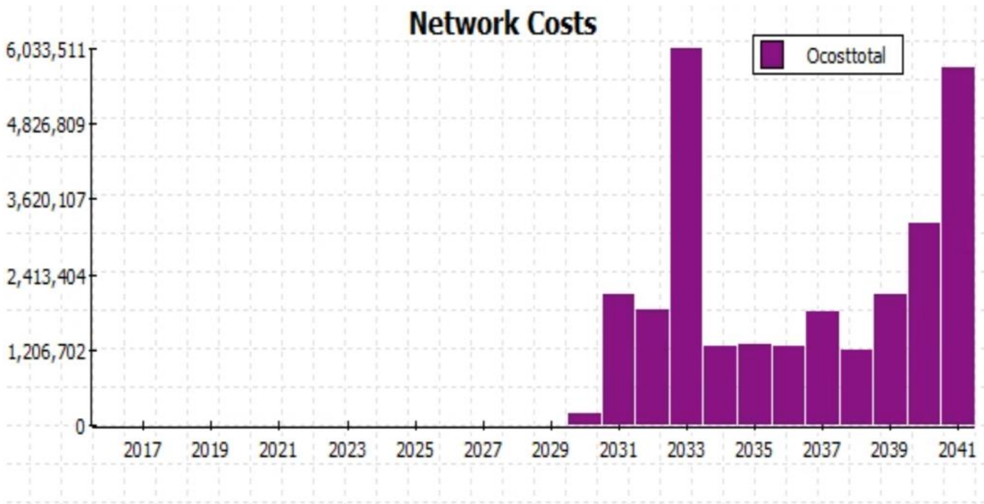
C- *Network Resilience Preparedness*



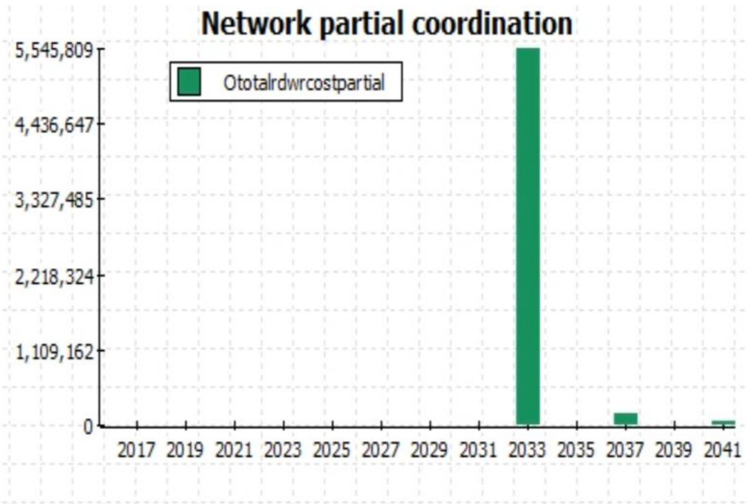
D – *Network repair time*



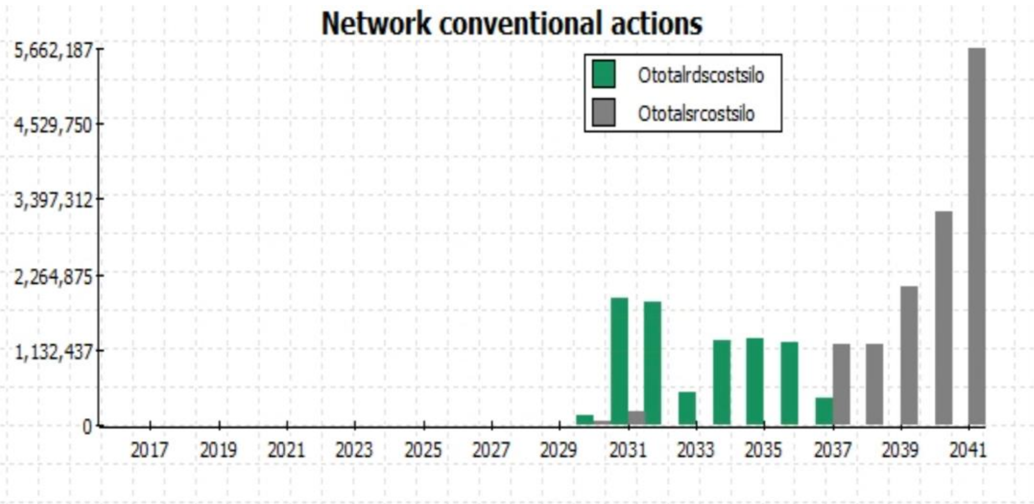
E – *Network space*



F – *Network direct and indirect costs*



G – *Network partial coordination costs*



H – *Network conventional costs*

Figure 5.22: *Scenario 6 – MOSEK Optimization results*

C. <u>Scenario 7 (Partially-coordinated – water and sewer + conventional roads)</u>

This scenario was carried out on the partially-coordinated water and sewer networks along with the conventional roads network. MOSEK linear optimization engine was used to reach an exact optimal intervention plan that meets the pre-defined contractual KPIs' thresholds across the planning horizon, as highlighted previously in sub-section 5.2.1.1. The objective of the partially-coordinated optimization was maximizing the improvement deviational variables across the planning horizon as discussed in Equation 3.109. The constraints were meeting the unacceptable performance and demand-capacity ratio thresholds defined earlier in Equations 3.111 and 3.112. The variables were the optimal intervention actions that need to be taken for each system within each corridor at every single point of time across the planning horizon as highlighted earlier in Equation 3.108. The optimization results could be summarized in Table **5-36** and Figure **5.23**. The results displayed a total of 338 intervention actions split into 89 for conventional road actions, 249 for partially-coordinated water and sewer (163 replacements with bigger diameter). This distribution is because the water and sewer networks were in a very good condition state and poor resilience preparedness. Thus, undertaking replacement actions for bigger diameter improved the resilience preparedness by 67% dropping from 75% to 8% demand-capacity ratio as displayed in Figure **5.23** (C). The average number of revisits for each corridor was 2 times, which shows the potential savings compared to the combined conventional scenario. The average number of interventions per year was 13 interventions for the 125 corridors, which results in an average disruption ratio of 11%. As shown in Figure **5.23** (A), the overall network was in a very good initial reliability of 84%. After running the optimization for 25 years, the reliability improved to 98% because of the undertaken replacement actions. Furthermore, as a result of the improved reliability, the risk index dropped from 20% to 2% as displayed in Figure **5.23** (B). The annual intervention time could be displayed in Figure **5.23** (D). The intervention program resulted in 1.6 million repair hours over the 25 years with an average of 1,200 repair hours per km per year, which reveals an NCR of 39% as opposed to the combined conventional scenario. Similarly, the annual intervention space could be displayed in Figure **5.23** (E). The intervention program resulted in 180,000 m^2 repair space over the 25 years with an average of 3.5 km per year. The annual intervention costs for conventional roads and sewer as well as the partially-coordinated water and sewer could be displayed in Figure **5.23** (F). The cost breakdown of the partially-coordinated intervention actions could be displayed in Figure **5.23** (G). Furthermore, the conventional road costs could be displayed in Figure **5.23** (H). The intervention program resulted in NPW of $31.6 million, equivalent to an EUAC of $1.6 million, for undertaking the conventional and partially-combined water and sewer intervention actions for the 53 km of Kindersley's road, water, and sewer networks. Those costs were broken-down to 72% for partially-coordinated intervention actions, amounting $22.8 million over the 25 years planning horizon, and 28% for conventional roads, amounting $8.8 million over the 25 years planning horizon. The average annual expenditures were $30,000 $/year/km.

As discussed earlier in the methodology, the coordination scenarios are compared with the combined conventional one to compute the potential savings in terms of the pre-defined multi-dimensional performance assessment indicators. Accordingly, the partially-coordinated water and sewer scenario was compared with the combined conventional scenario and the results are outlined in Table **5-29** and Table **5-30**. The results displayed huge temporal, spatio-temporal, and cost savings represented through a 39% NCR, 54% STIF, and 44% LIF. Furthermore, this coordination scenario displayed decent improvement in terms of condition (CIF=10%), resilience preparedness (RPIF=9%), and risk (RIF=10%). For the efficiency and effectiveness, the results displayed an IEF of 40% and IFF of 7%, which reflects less public disruptions (i.e. less disruption time, a fewer number of interventions) with longer corridor/asset operating times. Through combining the above-mentioned coordination savings, the partially-coordinated water and sewer scenario revealed an overall improvement of 27% as opposed to the combined conventional one.

Table 5-28: *Scenario 7 - Optimization summary results*

KPI	Combined network (Total)	Water and sewer	Roads conventional
Time (hours)	1,636,767	85,953	1,550,814
Space (m^2)	180,755	21,845	158,910
Cost – Equivalent Uniform Annual Cost (EUAC) ($)	$1,621,048	$1,168,893	$452,155
Cost – Net Present Worth (NPW) ($)	$31,648,453	$22,820,822	$8,827,630
# of intervention actions	338	249	89
Time per km per year (hours/km/year)	1,235	65	1,170

KPI	Combined network (Total)	Water and sewer	Roads conventional	
Cost per km per year ($//km/year)	$30,585.80	$22,054.58	$8,531.23	
Average repair length per year (km/year)	3.5	2.3	1.2	
Average number of interventions per year	13.52	9.96	3.56	
Ratio of interventions per year - number of annual interventions/number of corridors (%)	11%	8%	3%	
KPI	**Combined network (Total)**	**Roads**	**Water**	**Sewer**
Average Condition (%)	74%	11%	21%	66%
Average Risk (%)	30%	32%	28%	25%
Average Resilience (%)	73%	N/A	60%	86%

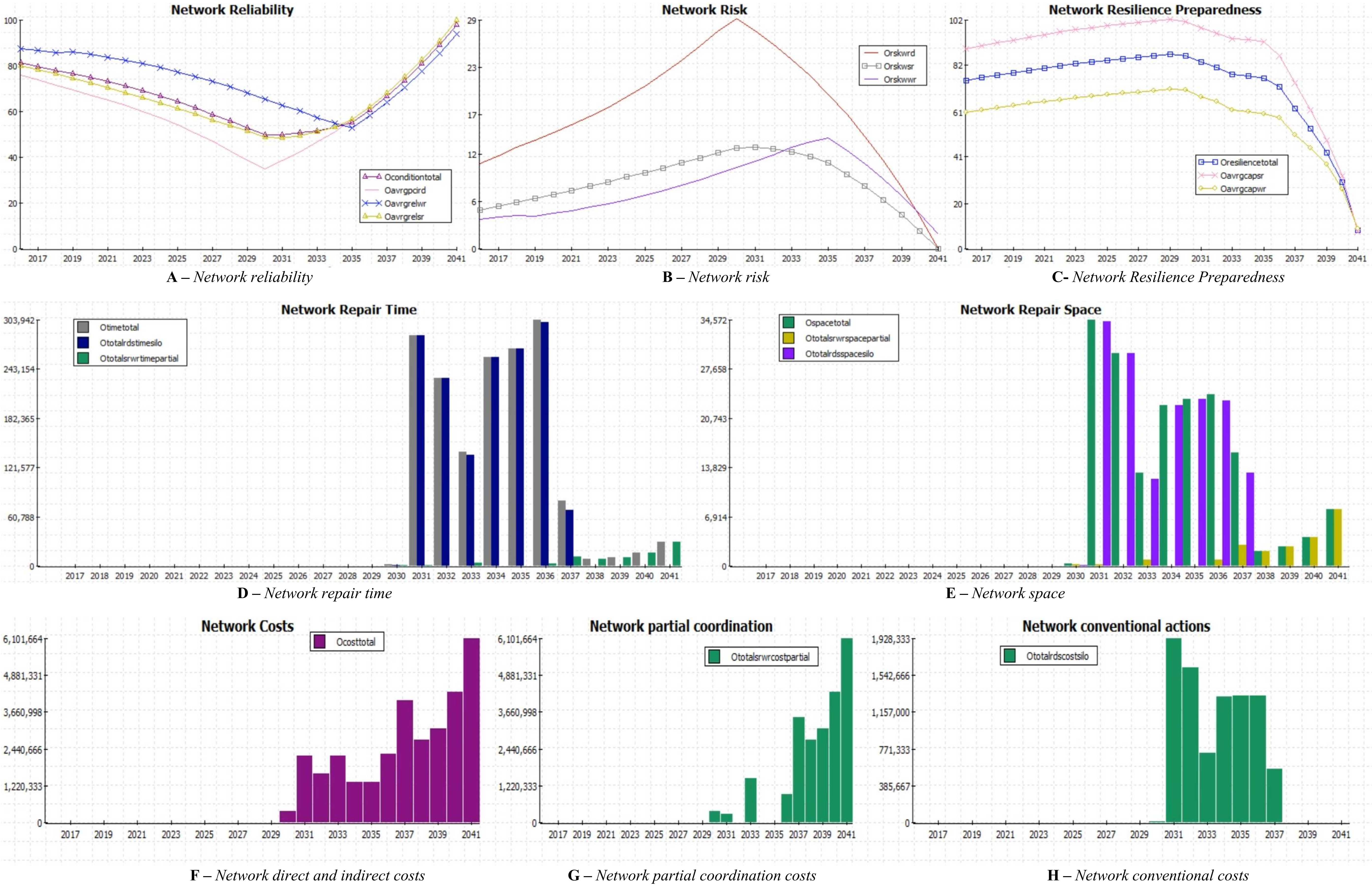
Table 5-29: *Scenario 7 – KPIs' comparison with combined conventional scenario*

KPI	Scenario 4 - Combined Conventional (Baseline)	Scenario 7 - Roads and sewer	Scenario 7 - Roads and sewer (Difference)
Time (hours)	2,673,608	1,636,767	39%
Space (m^2)	397,069	180,755	54%
Cost – Equivalent Uniform Annual Cost (EUAC) ($)	$2,918,743	$1,621,048	44%
Cost – Net Present Worth (NPW) ($)	$56,983,949	$31,648,453	44%
Average Condition (%)	66%	74%	10%
Average Risk (%)	36%	30%	10%
Average Resilience (%)	80%	73%	9%
# of intervention actions	560	338	40%
Time per km per year (hours/km/year)	2,018	1,235	39%
Cost per km per year ($//km/year)	$55,070.62	$30,585.80	44%
Average repair length per year (km/year)	5.2	3.5	32%

KPI	Scenario 4 - Combined Conventional (Baseline)	Scenario 7 - Roads and sewer	Scenario 7 - Roads and sewer (Difference)
Average number of interventions per year	22.4	13.52	40%
Ratio of interventions per year - number of annual interventions/number of corridors (%)	18%	11%	40%

Table 5-30: *Scenario 7 –Performance indicators' (Improvement deviational variables)*

Performance Indicator	KPI	Weights of importance (%)	Scenario 7 - Roads and sewer
Time	NCR	10%	39%
Space	STIF	10%	54%
Cost	LIF	20%	44%
Efficiency	IEF	5%	40%
Effectiveness	IFF	5%	7%
Condition	CIF	20%	10%
Resilience Preparedness	RPIF	10%	9%
Risk	RIF	20%	10%
Overall Improvement (%)			***27%***



A – *Network reliability*

B – *Network risk*

C- *Network Resilience Preparedness*

D – *Network repair time*

E – *Network space*

F – *Network direct and indirect costs*

G – *Network partial coordination costs*

H – *Network conventional costs*

Figure 5.23: *Scenario 7 – MOSEK Optimization results*

5.3.1.3 *Fully-Coordinated Optimization Results*

The fully-coordinated optimization aims at reaching an exact optimal intervention plan for the network on the basis of fully coordinating the interventions of the three networks altogether and allowing conventional interventions for the roads only given its shorter service life and thus, more frequent intervention actions. Similarly, the study was carried out across 25 years planning horizon. Scenario 8 was conducted for the fully-coordinated roads, water, and sewer. Finally, the fully-coordinated optimization results were compared with the optimization results of the combined conventional (scenario 4) and improvements were computed as will be discussed in the upcoming sub-section.

A. <u>Scenario 8 (Fully-coordinated - roads, water, and sewer)</u>

This scenario was carried out on the fully-coordinated roads, water, and sewer networks along with the conventional roads network. MOSEK linear optimization engine was used to reach an exact optimal intervention plan that meets the pre-defined contractual KPIs' thresholds across the planning horizon, as highlighted previously in sub-section 5.2.1.1. The objective of the fully-coordinated optimization was maximizing the improvement deviational variables across the planning horizon as discussed in Equation 3.109. The constraints were meeting the unacceptable performance and demand-capacity ratio thresholds defined earlier in Equations 3.111 and 3.112. The variables were the optimal intervention actions that need to be taken for each system within each corridor at every single point of time across the planning horizon as highlighted earlier in Equation 3.108. The optimization results could be summarized in Table **5-31** and Figure 5.24. The results displayed a total of 186 intervention actions split into 18 for conventional road actions, 168 fully-coordinated actions (22 replacement with bigger diameter). This distribution is because the water and sewer networks were in a very good condition state and poor resilience preparedness. Thus, undertaking replacement actions for bigger diameter improved the resilience preparedness by 29% dropping from 75% to 16% demand-capacity ratio as displayed in Figure 5.24 (C). The average number of revisits for each corridor was 1 time, which shows huge savings compared to the combined conventional scenario. The average number of interventions per year was 7 interventions for the 125 corridors, which results in the lowest average disruption ratio of 6%. As shown in Figure 5.24 (A), the overall network was in a very good initial reliability of 84%. After running the optimization for 25 years, the reliability improved to 98% because of the undertaken replacement actions. Furthermore, as a result of the improved reliability, the risk index dropped from 20% to 2% as displayed in Figure 5.24 (B). The annual intervention time could be displayed in Figure 5.24 (D). The intervention program resulted in 748,000 repair hours over the 25 years with an average of 565 repair hours per km per year, which reveals an NCR of 72% as opposed to the combined conventional scenario. Similarly, the annual intervention space could be displayed in Figure 5.24 (E). The intervention program resulted in 145,000 m^2 repair space over the 25 years with an average of 2.4 km per year. The annual intervention costs for conventional roads as well as the fully-coordinated road, water, and sewer could be displayed in Figure 5.24 (F). The cost breakdown of the fully-coordinated intervention actions could be displayed in Figure 5.24 (G). Furthermore, the conventional road costs could be displayed in Figure 5.24 (H). The intervention program resulted in NPW of $29 million, equivalent to an EUAC of $1.5 million, for undertaking the conventional roads and fully-coordinated road, water, and sewer intervention actions for the 53 km of Kindersley's road, water, and sewer networks. Those costs were broken-down to 95% for fully-coordinated intervention actions, amounting $27.6 million over the 25 years planning horizon, and 5% for conventional roads, amounting $1.4 million over the 25 years planning horizon. The average annual expenditures were $27,000 $/year/km.

As discussed earlier in the methodology, the coordination scenarios are compared with the combined conventional one to compute the potential savings in terms of the pre-defined multi-dimensional performance assessment indicators. Accordingly, the fully-coordinated road, water, and sewer scenario was compared with the combined conventional scenario and the results are outlined in Table **5-32** and Table **5-33**. The results displayed huge temporal, spatio-temporal, and cost savings represented through a 72% NCR, 63% STIF, and 48% LIF. Furthermore, this coordination scenario displayed fair improvement in terms of condition (CIF=1%), resilience preparedness (RPIF=14%), and risk (RIF=5%). For the efficiency and effectiveness, the results displayed an IEF of 67% and IFF of 9%, which reflects less public disruptions (i.e. less disruption time, a fewer number of interventions) with longer corridor/asset operating times. Through combining the above-mentioned coordination savings, the fully-coordinated roads, water, and sewer scenario revealed an overall improvement of 29% as opposed to the combined conventional one.

Table 5-31: *Scenario 8 - Optimization summary results*

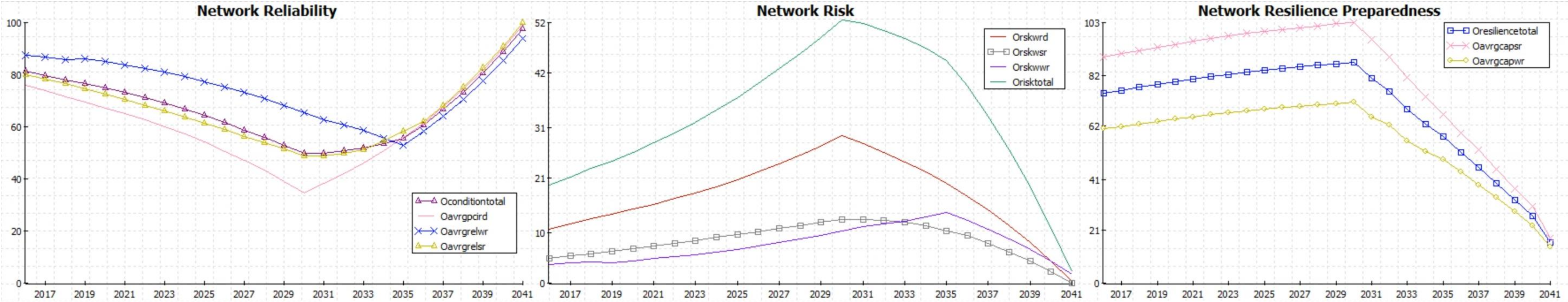
KPI	Combined network (Total)	Roads, water and sewer	Roads conventional	
Time (hours)	748,074	244,467	503,604	
Space (m^2)	145,467	60,518	84,948	
Cost – Equivalent Uniform Annual Cost (EUAC) ($)	$1,529,741	$1,456,329	$73,412	
Cost – Net Present Worth (NPW) ($)	$29,865,841	$28,432,579	$1,433,261	
# of intervention actions	186	168	18	
Time per km per year (hours/km/year)	565	185	380	
Cost per km per year ($//km/year)	$28,863.05	$27,477.91	$1,385.14	
Average repair length per year (km/year)	2.4	2.2	0.2	
Average number of interventions per year	7.44	6.72	0.72	
Ratio of interventions per year - number of annual interventions/number of corridors (%)	6%	5%	1%	
KPI	**Combined network (Total)**	**Roads**	**Water**	**Sewer**
Average Condition (%)	67%	61%	74%	66%
Average Risk (%)	34%	18%	8%	8%
Average Resilience (%)	69%	N/A	57%	81%

Table 5-32: *Scenario 8 – KPIs' comparison with combined conventional scenario*

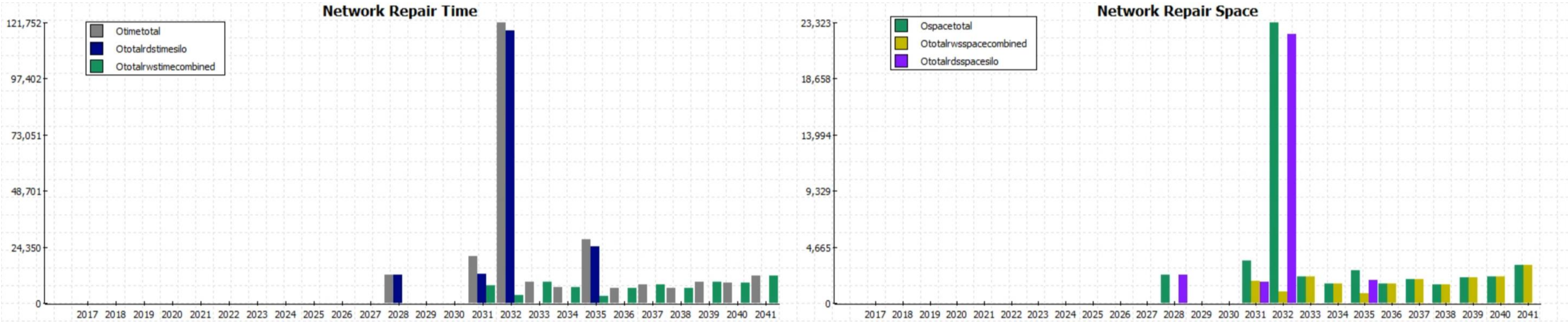
KPI	Scenario 4 - Combined Conventional (Baseline)	Scenario 8 - Fully combined	Scenario 8 - Fully combined (Difference)
Time (hours)	2,673,608	748,074	72%
Space (m^2)	397,069	145,467	63%
Cost – Equivalent Uniform Annual Cost (EUAC) ($)	$2,918,743	$1,529,741	48%
Cost – Net Present Worth (NPW) ($)	$56,983,949	$29,865,841	48%
Average Condition (%)	66%	67%	1%
Average Risk (%)	36%	34%	5%
Average Resilience (%)	80%	69%	14%
# of intervention actions	560	186	67%
Time per km per year (hours/km/year)	2,018	565	72%
Cost per km per year ($//km/year)	$55,070.62	$28,863.05	48%
Average repair length per year (km/year)	5.2	2.4	54%
Average number of interventions per year	22.4	7.44	67%
Ratio of interventions per year - number of annual interventions/number of corridors (%)	18%	6%	67%

Table 5-33: *Scenario 8 –Performance indicators' (Improvement deviational variables)*

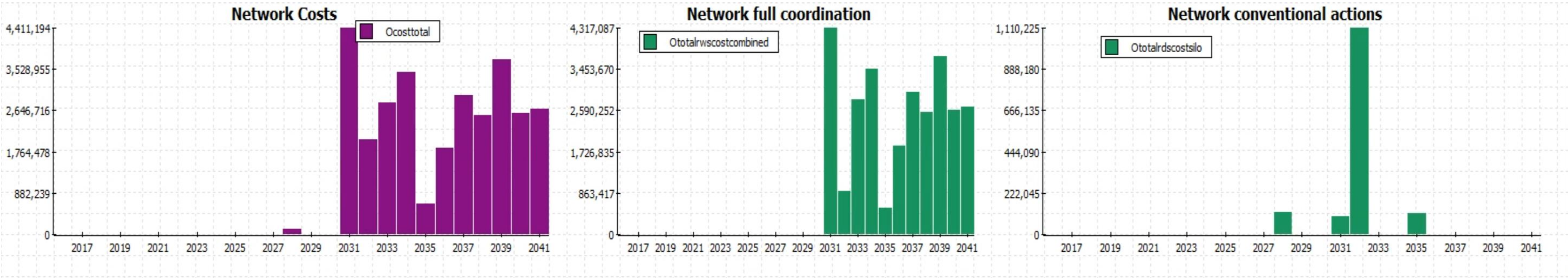
Performance Indicator	KPI	Weights of importance (%)	Scenario 8 - Fully combined
Time	NCR	10%	72%
Space	STIF	10%	63%
Cost	LIF	20%	48%
Efficiency	IEF	5%	67%
Effectiveness	IFF	5%	9%
Condition	CIF	20%	1%
Resilience Preparedness	RPIF	10%	14%
Risk	RIF	20%	5%
Overall Improvement (%)			***29%***



A – *Network reliability* **B** – *Network risk* **C-** *Network Resilience Preparedness*



D – *Network repair time* **E** – *Network space*



F – *Network direct and indirect costs* **G** – *Network full coordination costs* **H** – *Network conventional costs*

Figure 5.24: *Scenario 8 – MOSEK Optimization results*

5.3.2 *Summary results*

The optimization results for the 8 scenarios were summarized and outlined in Table **5-34**, Table **5-35**, Table **5-36**, and Table **5-37**. As discussed earlier, the conventional optimization scenarios displayed the results of undertaking single asset-based intervention. The conventional results displayed a larger number of interventions compared to the coordinated scenarios. The condition, risk, and resilience were slightly better for the coordinated scenario as opposed to the conventional one. The time, space consumption, and cost experienced a major change as the common or duplicated activities were carried out once instead of n_s times as discussed earlier in the methodology. Furthermore, the coordinated scenarios were compared with the combined conventional scenario. The performance assessment improvement results showed the full-coordination scenario as the best scenario with 29% savings, followed by the partially-coordinated water and sewer with 27%. Then, the partially-coordinated roads and water took place with 22% and finally, the partially-coordinated roads and sewer came at the end with only 9%. The detailed breakdown of the overall improvement, as well as the improvement computations, were thoroughly discussed in the previous sub-sections.

Table 5-34: *Conventional optimization summary results - Scenarios 1 through 3*

KPI	Roads (excluding crack sealing)	Roads (including crack sealing)	Scenario 2 - Water	Scenario 3 - Sewer	Combined Network (excluding crack sealing)
Time (hours)	3,620,580	3,090,887	182,878	100,481	3,903,939
Space (m^2)	285,054	250,009	71,156	39,213	395,424
Cost – Equivalent Uniform Annual Cost (EUAC) ($)	$817,260	$683,249	$702,248	$1,025,412	2,544,921
Cost – Net Present Worth (NPW) ($)	$15,955,745	$13,339,373	$13,710,317	$20,019,589	49,685,651
Average Condition (%)	67%	65%	74%	64%	68%
Average Risk (%)	33%	35%	26%	36%	32%
Average Resilience (%)	N/A	N/A	57%	96%	76%
# of intervention actions	444	766	303	197	944
Time per km per year (hours/km/year)	2,733	2,333	138	76	2,946
Cost per km per year ($//km/year)	$15,420.00	$12,891.48	$13,249.97	$19,347.40	48,017
Average repair length per year (km/year)	3.6	3.7	5.4	3.0	12
Average number of interventions per year	17.76	30.64	12.12	7.88	38
Ratio of interventions per year - number of annual interventions/number of corridors (%)	14%	25%	10%	6%	30%

Table 5-35: *Combined conventional and coordinated optimization summary results - Scenarios 4 through 8*

KPI	Scenario 4 - Combined Conventional (Baseline)	Scenario 5 - Roads and sewer	Scenario 6 - Roads and water	Scenario 7 – Water and sewer	Scenario 8 - Fully combined
Time (hours)	2,673,608	1,093,561	1,614,876	1,636,767	748,074
Space (m^2)	397,069	282,758	195,432	180,755	145,467
Cost – Equivalent Uniform Annual Cost (EUAC) ($)	$2,918,743	$3,569,007	$1,436,639	$1,621,048	$1,529,741
Cost – Net Present Worth (NPW) ($)	$56,983,949	$69,679,348	$28,048,165	$31,648,453	$29,865,841
Average Condition (%)	66%	67%	67%	74%	67%
Average Risk (%)	36%	34%	34%	12%	34%
Average Resilience (%)	80%	75%	80%	73%	69%
# of intervention actions	560	271	316	338	186
Time per km per year (hours/km/year)	2,018	825	1,219	1,235	565
Cost per km per year ($//km/year)	$55,070.62	$67,339.75	$27,106.40	$30,585.80	$28,863.05
Average repair length per year (km/year)	5.2	3.4	3.4	3.5	2.4
Average number of interventions per year	22.4	10.84	12.64	13.52	7.44
Ratio of interventions per year - number of annual interventions/number of corridors (%)	18%	9%	10%	11%	6%

Table 5-36: *Combined conventional and coordinated improvement (%) - Scenarios 4 through 8*

KPI	Scenario 4 - Combined Conventional (Baseline)	Scenario 5 - Roads and sewer	Scenario 6 - Roads and water	Scenario 7 - Roads and sewer	Scenario 8 - Fully combined
Time (hours)	0%	59%	40%	39%	72%
Space (m^2)	0%	29%	51%	54%	63%
Cost – Equivalent Uniform Annual Cost (EUAC) ($)	0%	-22%	51%	44%	48%
Cost – Net Present Worth (NPW) ($)	0%	-22%	51%	44%	48%
Average Condition (%)	0%	1%	0%	10%	1%
Average Risk (%)	0%	5%	4%	65%	5%
Average Resilience (%)	0%	6%	0%	9%	14%
# of intervention actions	0%	52%	44%	40%	67%
Time per km per year (hours/km/year)	0%	59%	40%	39%	72%
Cost per km per year ($//km/year)	0%	-22%	51%	44%	48%
Average repair length per year (km/year)	0%	34%	34%	32%	53%
Average number of interventions per year	0%	52%	44%	40%	67%
Ratio of interventions per year - number of annual interventions/number of corridors (%)	0%	52%	44%	40%	67%

Table 5-37: *KPIs' summary results for partially and fully coordinated scenarios – Scenario 5 through 8*

Performance Indicator	KPI	Weights of importance (%)	Scenario 5 - Roads and sewer	Scenario 6 - Roads and water	Scenario 7 - Water and sewer	Scenario 8 - Fully combined
Time	NCR	10%	59%	40%	39%	72%
Space	STIF	10%	29%	51%	54%	63%
Cost	LIF	20%	-22%	51%	44%	48%
Efficiency	IEF	5%	52%	44%	40%	67%
Effectiveness	IFF	5%	2%	5%	7%	9%
Condition	CIF	20%	1%	0%	10%	1%
Resilience Preparedness	RPIF	10%	6%	0%	9%	14%
Risk	RIF	20%	5%	4%	10%	5%
Overall Improvement (%)			***9%***	***22%***	***27%***	***29%***

5.3.3 *Sensitivity Analysis*

Sensitivity analysis is performed to study and verify the sensitivity of the increasing or decreasing the minimally acceptable reliability thresholds on the other KPIs'. It can answer many what-if questions such as: "Should we pay more for enhancing the network reliability?" And if the answer is yes, "what is the cost premium between the proposed intervention program and the optimal intervention program?" The sensitivity analysis was undertaken only for the fully-coordinated scenario and four new optimization cases ranging between -20% and +20% with 10% increments were run. The optimization results of the four cases could be displayed in Table **5-38**, Table **5-39**, Table **5-40**, Table **5-41**, Figure 5.25, Figure 5.26, Figure 5.27, and Figure 5.28 for cases 1 (-10%), 2 (-20%), 3 (10%), and 4 (20%) respectively. Furthermore, the improvement deviational variables of the four scenarios were computed as outlined in Table **5-42**, Table **5-43**, and Table **5-44**. Thenceforth, the sensitivity analysis was carried out to compare the cases' improvement deviations variables outcomes with the baseline case (scenario 8) and accordingly plot the difference as outlined in Table **5-45** and Table 5-46.

The system showed to be very sensitive to changes in the reliability threshold as shown in Table 5-47 and Figure 5.29. For instance, decreasing the reliability threshold by 20% revealed 86% less time, 85% less space, 7% less cost, 33% improved efficiency, 3% effectiveness, 10% decline in the average network reliability and resilience preparedness, 24% higher risk as a result of the declined reliability, and 3% decline in the overall improvement as opposed to the baseline fully-coordinated scenario. Similarly, the other scenarios were carried out and the results were plotted in Figure 5.29. In summary, slight changes in the reliability drastically affect the other KPIs. The repair time and efficiency showed to be the most sensitive items to the changes in the reliability thresholds. However, the effectiveness showed to be the least sensitive item to the changes in the reliability thresholds.

Table 5-38: *Sensitivity analysis (-10%) - Optimization summary results*

KPI	Combined network (Total)	Roads, water and sewer	Roads conventional
Time (hours)	153,560	77,318	76,242
Space (m^2)	30,414	18,879	76,242
Cost – Equivalent Uniform Annual Cost (EUAC) ($)	$1,455,275	$1,426,658	$28,617

KPI	Combined network (Total)	Roads, water and sewer	Roads conventional	
Cost – Net Present Worth (NPW) ($)	$28,412,004	$27,853,302	$558,703	
# of intervention actions	143	7	136	
Time per km per year (hours/km/year)	116	58	58	
Cost per km per year ($//km/year)	$27,458.02	$26,918.08	$539.94	
Average repair length per year (km/year)	2.2	2.1	0.1	
Average number of interventions per year	5.72	0.28	5.44	
Ratio of interventions per year - number of annual interventions/number of corridors (%)	5%	0%	4%	
KPI	**Combined network (Total)**	**Roads**	**Water**	**Sewer**
Average Condition (%)	62%	54%	71%	62%
Average Risk (%)	39%	21%	9%	10%
Average Resilience (%)	73%	N/A	60%	87%

Table 5-39: *Sensitivity analysis (-20%) - Optimization summary results*

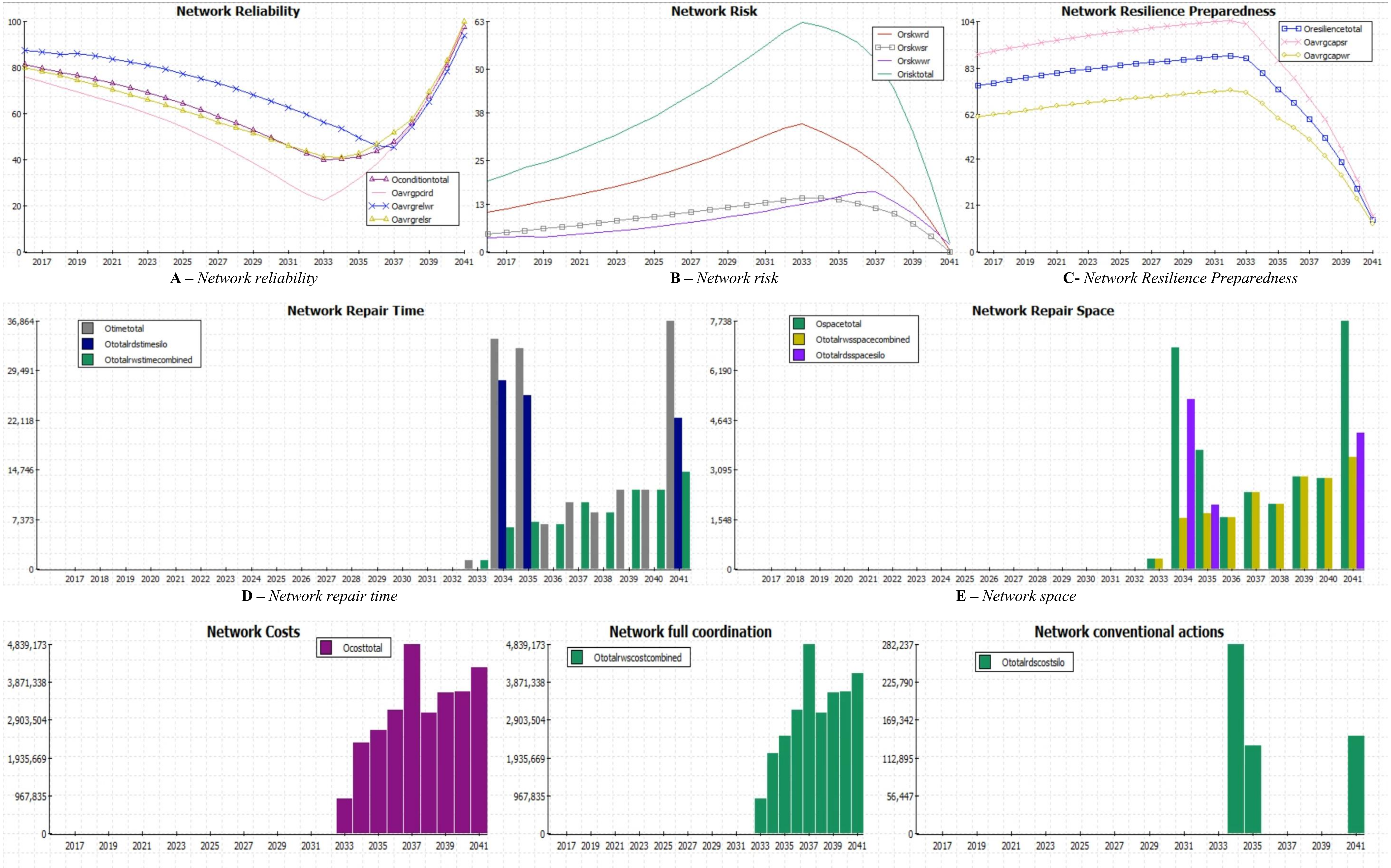
KPI	Combined network (Total)	Roads, water and sewer	Roads conventional	
Time (hours)	104,200	78,432	25,768	
Space (m^2)	21,132	19,141	25,768	
Cost – Equivalent Uniform Annual Cost (EUAC) ($)	$1,421,309	$1,414,094	$7,214	
Cost – Net Present Worth (NPW) ($)	$27,748,859	$27,608,010	$140,849	
# of intervention actions	134	133	1	
Time per km per year (hours/km/year)	79	59	19	
Cost per km per year ($//km/year)	$26,817.15	$26,681.03	$136.12	
Average repair length per year (km/year)	2.12	2.10	0.02	
Average number of interventions per year	5.36	5.32	0.04	
Ratio of interventions per year - number of annual interventions/number of corridors (%)	4%	4%	0%	
KPI	**Combined network (Total)**	**Roads**	**Water**	**Sewer**
Average Condition (%)	60%	50%	70%	60%
Average Risk (%)	42%	23%	9%	10%
Average Resilience (%)	76%	N/A	63%	90%

Table 5-40: *Sensitivity analysis (10%) - Optimization summary results*

KPI	Combined network (Total)	Roads, water and sewer	Roads conventional	
Time (hours)	2,288,205	53,727	2,234,483	
Space (m^2)	338,769	13,670	2,234,483	
Cost – Equivalent Uniform Annual Cost (EUAC) ($)	$1,565,663	$855,041	$710,622	
Cost – Net Present Worth (NPW) ($)	$30,567,146	$16,693,351	$13,873,796	
# of intervention actions	582	191	391	
Time per km per year (hours/km/year)	1,727	41	1,686	
Cost per km per year ($//km/year)	$29,540.80	$16,132.84	$13,407.96	
Average repair length per year (km/year)	3.8	1.4	2.5	
Average number of interventions per year	23.28	7.64	15.64	
Ratio of interventions per year - number of annual interventions/number of corridors (%)	19%	6%	13%	
KPI	**Combined network (Total)**	**Roads**	**Water**	**Sewer**
Average Condition (%)	85%	84%	89%	83%
Average Risk (%)	15%	7%	3%	4%
Average Resilience (%)	61%	N/A	49%	73%

Table 5-41: *Sensitivity analysis (20%) - Optimization summary results*

KPI	Combined network (Total)	Roads, water and sewer	Roads conventional	
Time (hours)	730,503	87,983	642,521	
Space (m^2)	123,753	22,351	642,521	
Cost – Equivalent Uniform Annual Cost (EUAC) ($)	$1,707,682	$1,465,890	$241,792	
Cost – Net Present Worth (NPW) ($)	$33,339,854	$28,619,247	$4,720,608	
# of intervention actions	345	259	86	
Time per km per year (hours/km/year)	551	66	485	
Cost per km per year ($//km/year)	$32,220.41	$27,658.31	$4,562.11	
Average repair length per year (km/year)	3.2	2.5	0.8	
Average number of interventions per year	13.8	10.36	3.44	
Ratio of interventions per year - number of annual interventions/number of corridors (%)	11%	8%	3%	
KPI	**Combined network (Total)**	**Roads**	**Water**	**Sewer**
Average Condition (%)	75%	72%	79%	74%
Average Risk (%)	26%	13%	6%	6%
Average Resilience (%)	63%	N/A	51%	75%



A – *Network reliability*

B – *Network risk*

C- *Network Resilience Preparedness*

D – *Network repair time*

E – *Network space*

F – *Network direct and indirect costs*

G – *Network full coordination costs*

H – *Network conventional costs*

Figure 5.25: *Sensitivity analysis (-10%) – MOSEK Optimization results*

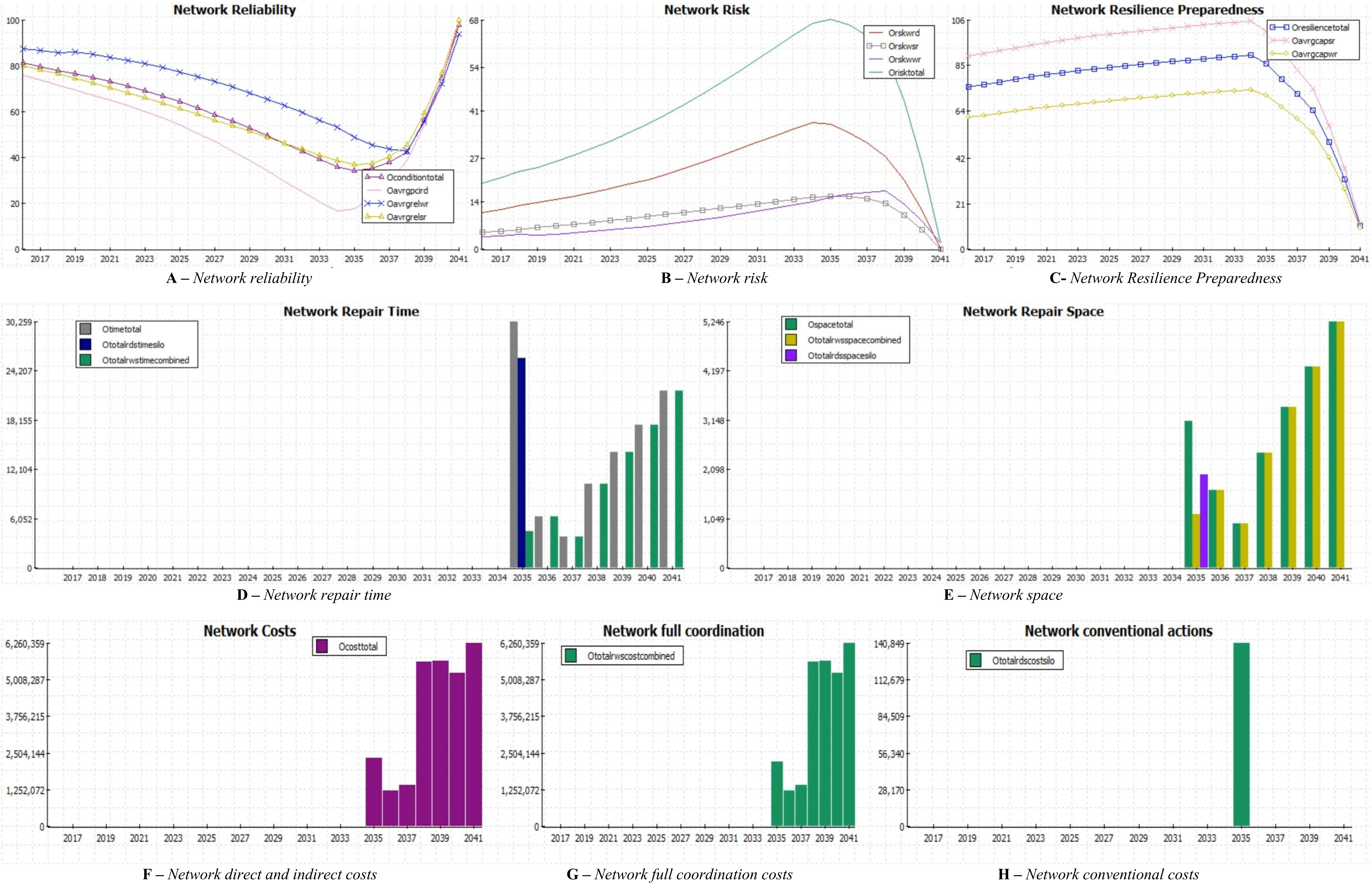
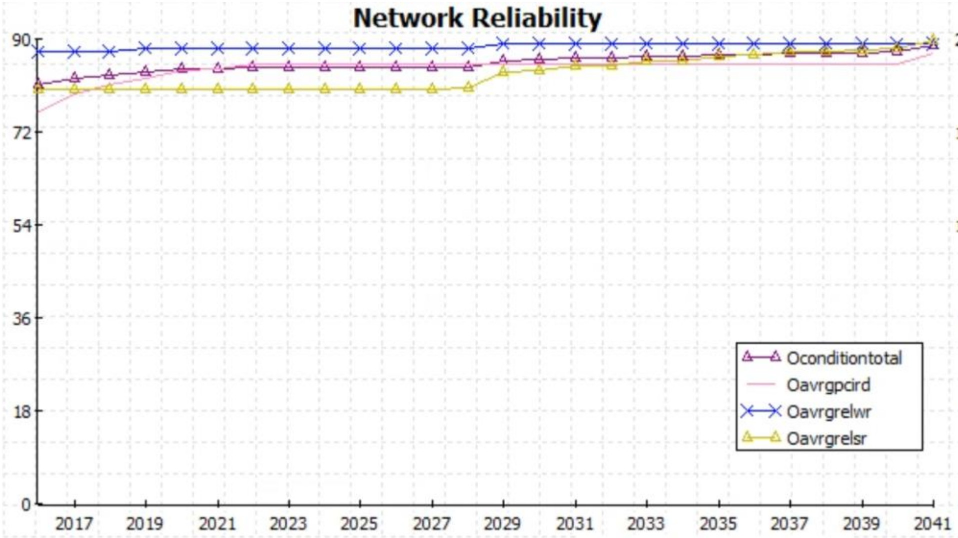
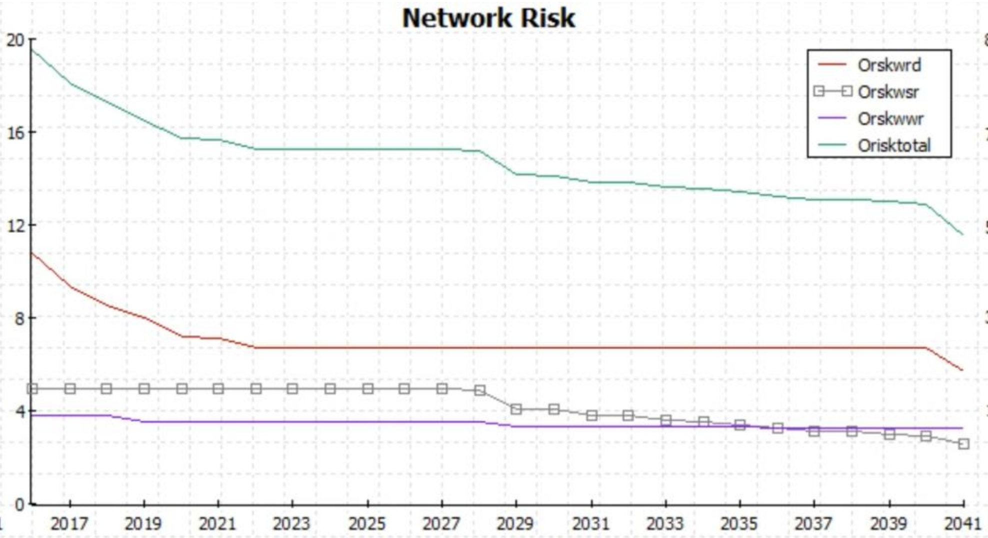


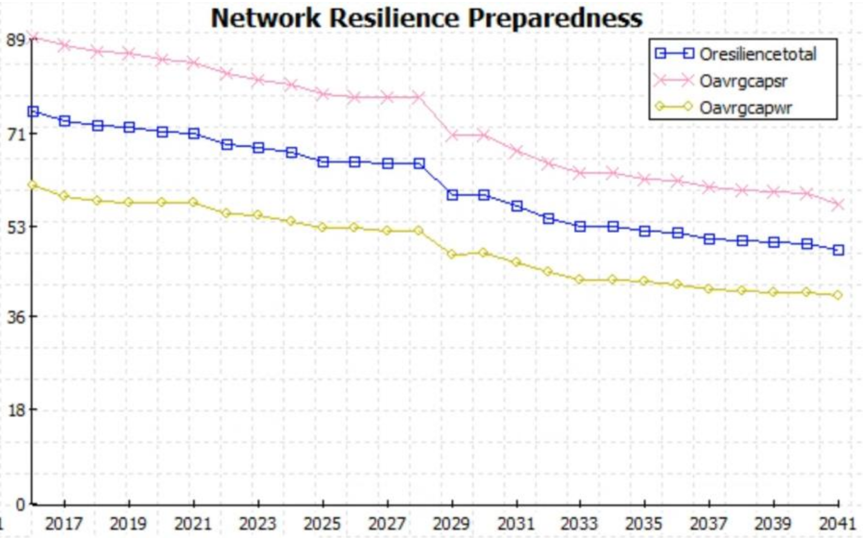
Figure 5.26: *Sensitivity analysis (-20%) – MOSEK Optimization results*



A – *Network reliability*



B – *Network risk*



C- *Network Resilience Preparedness*

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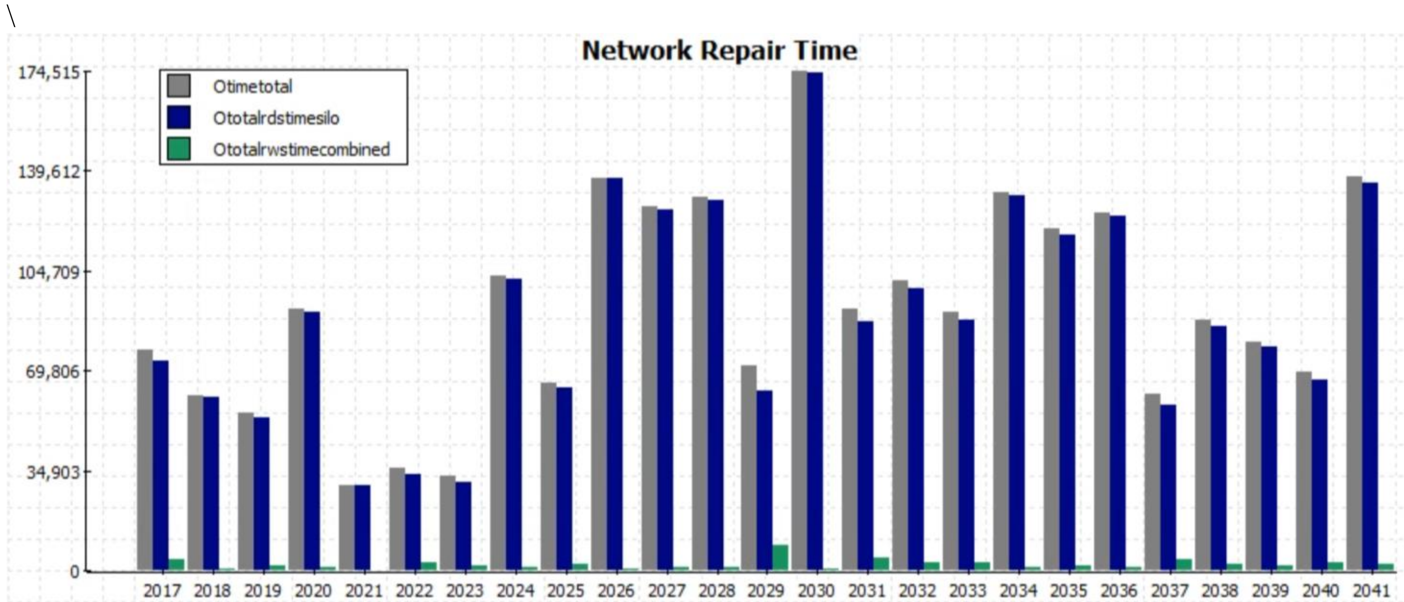
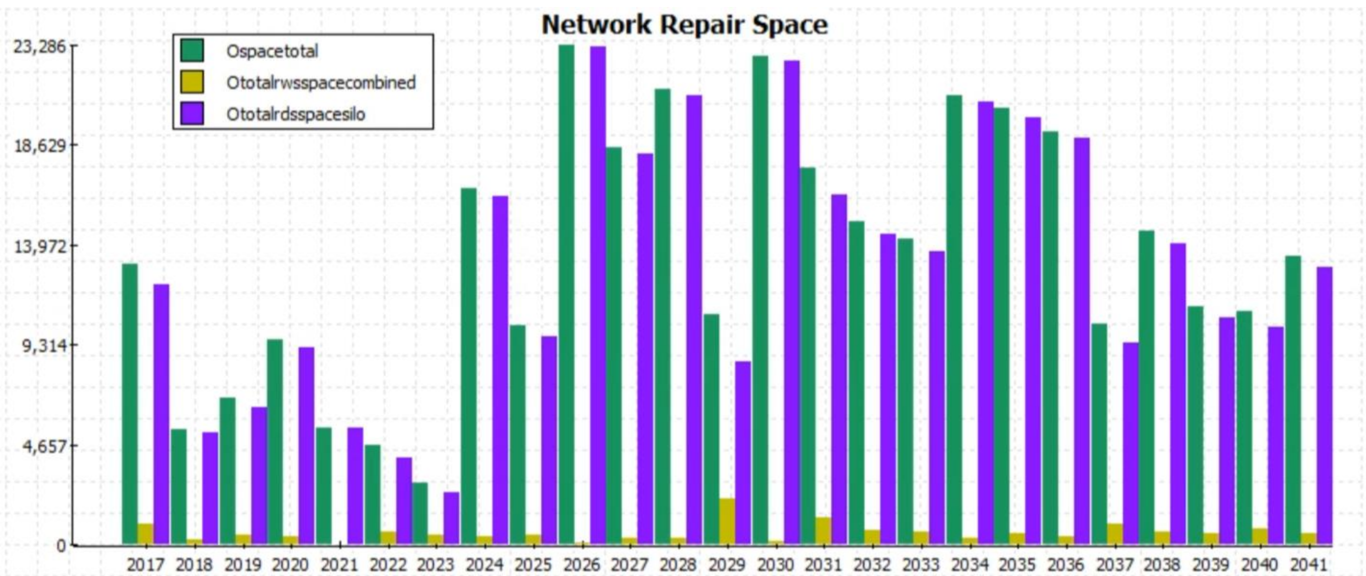
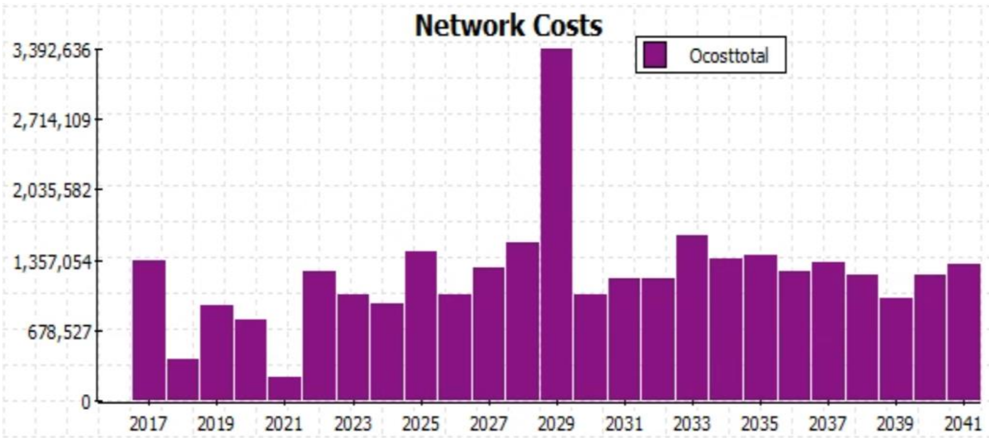
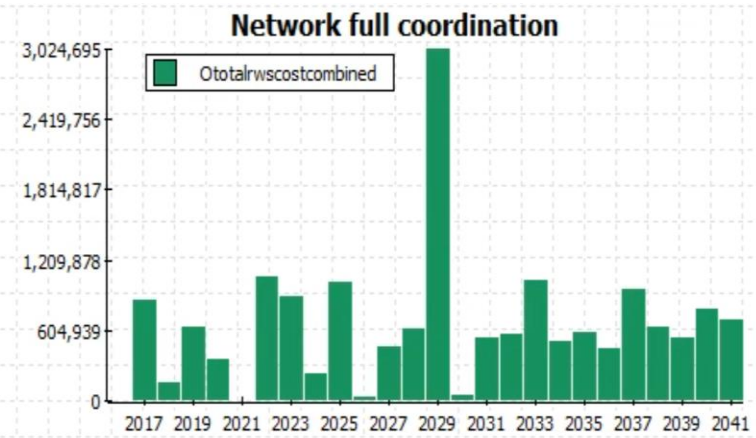


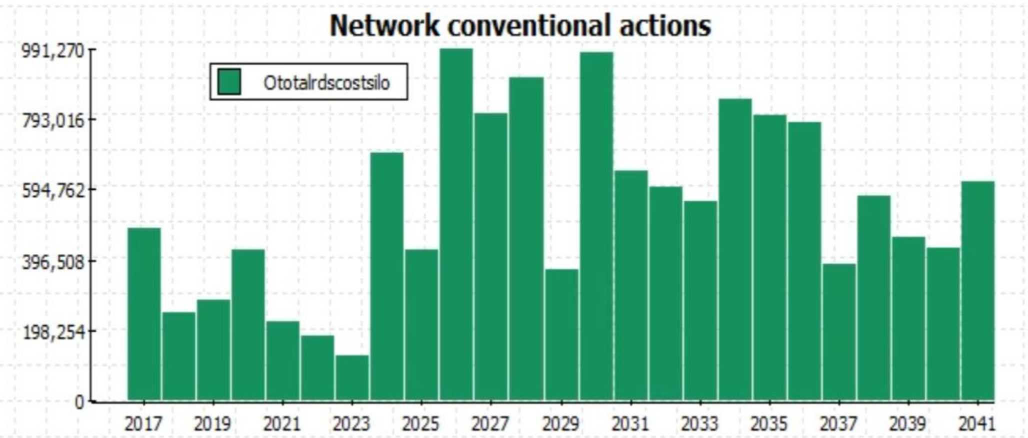
D – *Network repair time*



E – *Network space*





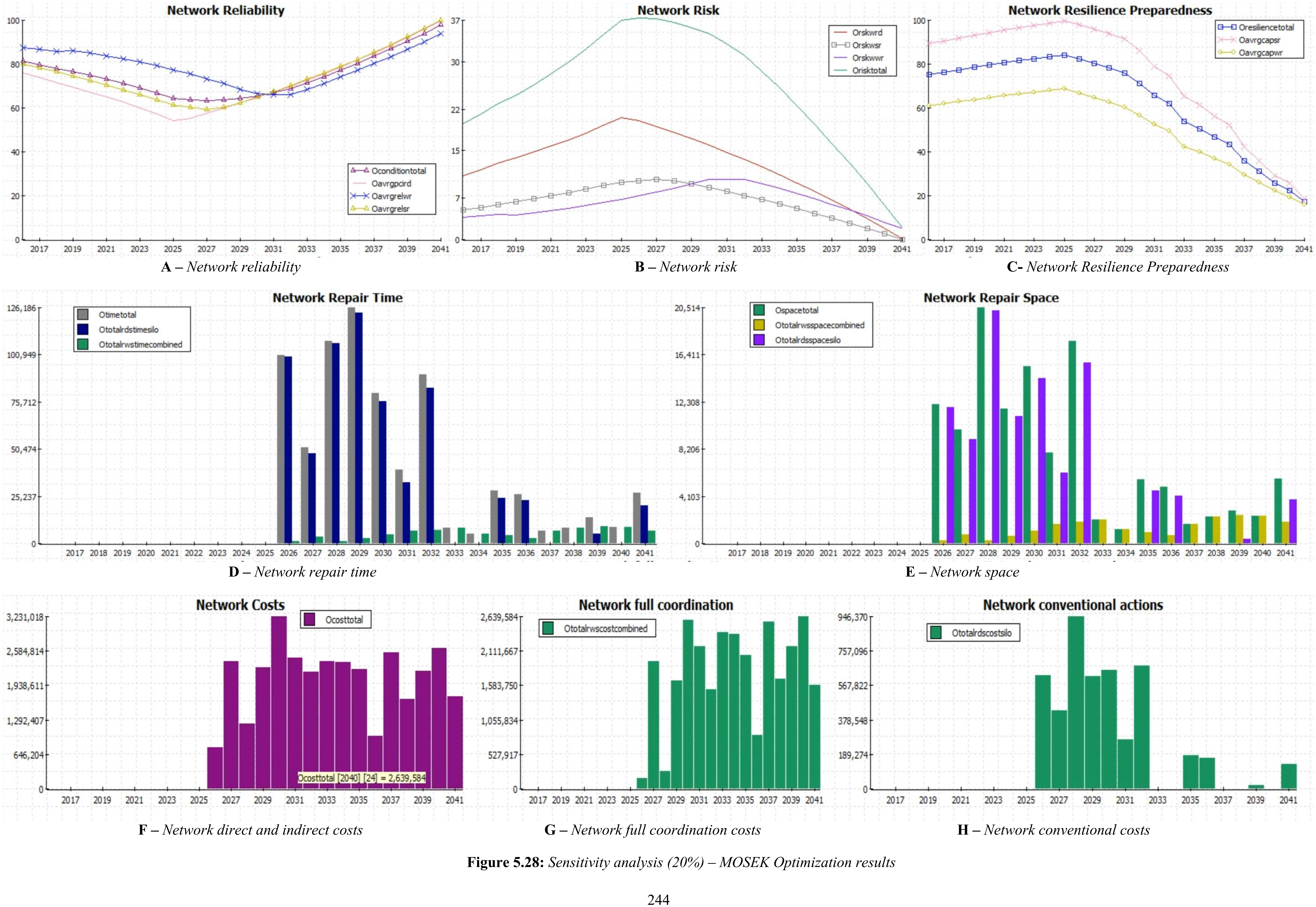


F – *Network direct and indirect costs*

G – *Network full coordination costs*

H – *Network conventional costs*

Figure 5.27: *Sensitivity analysis (10%) – MOSEK Optimization results*



A – *Network reliability*

B – *Network risk*

C- *Network Resilience Preparedness*

D – *Network repair time*

E – *Network space*

F – *Network direct and indirect costs*

G – *Network full coordination costs*

H – *Network conventional costs*

Figure 5.28: *Sensitivity analysis (20%) – MOSEK Optimization results*

Table 5-42: *Sensitivity analysis cases' optimization summary results – Town of Kindersley*

KPI	Scenario 4 - Combined Conventional	Case 1 (-20%)	Case 2 (-10%)	Baseline (Scenario 8)	Case 3 (10%)	Case 4 (20%)
Time (hours)	2,673,608	104,200	153,560	748,074	2,288,205	730,503
Space (m^2)	397,069	21,132	30,414	145,467	338,769	123,753
Cost – Equivalent Uniform Annual Cost (EUAC) ($)	$2,918,743	$1,421,309	$1,455,275	$1,529,741	$1,565,663	$1,707,682
Cost – Net Present Worth (NPW) ($)	$56,983,949	$27,748,859	$28,412,004	$29,865,841	$30,567,146	$33,339,854
Average Condition (%)	66%	60%	62%	67%	85%	75%
Average Risk (%)	36%	42%	39%	34%	15%	26%
Average Resilience (%)	80%	76%	73%	69%	61%	63%
# of intervention actions	560	134	143	186	582	345
Time per km per year (hours/km/year)	2,018	78.64150943	116	565	1726.94717	551.3230189
Cost per km per year ($//km/year)	$55,070.62	$26,817.15	$27,458.02	$28,863.05	$29,540.80	$32,220.41
Average repair length per year (km/year)	5.2348	2.11864	2.15864	2.44004	3.84496	3.22764
Average number of interventions per year	22.4	5.36	5.72	7.44	23.28	13.8
Ratio of interventions per year - number of annual interventions/number of corridors (%)	18%	4%	5%	6%	19%	11%

Table 5-43: *Sensitivity analysis cases' improvement (%) – Town of Kindersley*

KPI	Scenario 4 - Combined Conventional	Case 1 (-20%)	Case 2 (-10%)	Baseline (Scenario 8)	Case 3 (10%)	Case 4 (20%)
Time (hours)	0%	96%	94%	72%	14%	73%
Space (m^2)	0%	95%	92%	63%	15%	69%
Cost – Equivalent Uniform Annual Cost (EUAC) ($)	0%	51%	50%	48%	46%	41%
Cost – Net Present Worth (NPW) ($)	0%	51%	50%	48%	46%	41%
Average Condition (%)	0%	-9%	-6%	2%	29%	14%
Average Risk (%)	0%	-17%	-8%	6%	58%	28%
Average Resilience (%)	0%	5%	9%	14%	24%	21%
# of intervention actions	0%	76%	74%	67%	-4%	38%
Time per km per year (hours/km/year)	0%	96%	94%	72%	14%	73%
Cost per km per year ($//km/year)	0%	51%	50%	48%	46%	41%
Average repair length per year (km/year)	0%	60%	59%	53%	27%	38%
Average number of interventions per year	0%	76%	74%	67%	-4%	38%
Ratio of interventions per year - number of annual interventions/number of corridors (%)	0%	78%	72%	67%	-6%	39%

Table 5-44: *Sensitivity analysis cases – Improvement deviational variables – Town of Kindersley*

Performance Indicator	KPI	Weights of importance (%)	Case 1 (-20%)	Case 2 (-10%)	Baseline (Scenario 8)	Case 3 (10%)	Case 4 (20%)
Time	NCR	10%	96%	94%	72%	14%	73%
Space	STIF	10%	95%	92%	63%	15%	69%
Cost	LIF	20%	51%	50%	48%	46%	41%
Efficiency	IEF	5%	78%	72%	67%	-6%	39%
Effectiveness	IFF	5%	3%	5%	9%	8%	10%
Condition	CIF	20%	-9%	-6%	1%	29%	14%
Resilience Preparedness	RPIF	10%	5%	9%	14%	24%	21%
Risk	RIF	20%	-17%	-8%	5%	58%	28%
Overall deviation (%)			***28%***	***30%***	***29%***	***31%***	***29%***

Table 5-45: *KPIs' summary deviations from the baseline scenario 8 – Town of Kindersley*

KPI	Case 1 (-20%)	Case 2 (-10%)	Baseline (Scenario 8)	Case 3 (10%)	Case 4 (20%)
Time (hours)	643,874	594,514	0	-1,540,131	17,571
Space (m^2)	124,335	115,053	0	-193,302	21,714
Cost – Equivalent Uniform Annual Cost (EUAC) ($)	$108,433	$74,466	$0	-$35,921	-$177,940
Cost – Net Present Worth (NPW) ($)	$2,116,982	$1,453,837	$0	-$701,305	-$3,474,013
Average Condition (%)	-7%	-5%	0%	18%	8%
Average Risk (%)	-8%	-5%	0%	19%	8%
Average Resilience (%)	-7%	-5%	0%	8%	6%
# of intervention actions	52	43	0	-396	-159
Time per km per year (hours/km/year)	486	449	0	-1,162	13
Cost per km per year ($//km/year)	$2,045.90	$1,405.02	$0.00	-$677.76	-$3,357.37
Average repair length per year (km/year)	0.3214	0.2814	0	-1.40492	-0.7876
Average number of interventions per year	2.08	1.72	0	-15.84	-6.36
Ratio of interventions per year - number of annual interventions/number of corridors (%)	2%	1%	0%	-13%	-5%

Table 5-46: *KPIs' summary deviations (%) from the baseline scenario 8 – Town of Kindersley*

KPI	Case 1 (-20%)	Case 2 (-10%)	Baseline (Scenario 8)	Case 3 (10%)	Case 4 (20%)
Time (hours)	86%	79%	0%	-206%	2%
Space (m^2)	85%	79%	0%	-133%	15%
Cost – Equivalent Uniform Annual Cost (EUAC) ($)	7%	5%	0%	-2%	-12%
Cost – Net Present Worth (NPW) ($)	7%	5%	0%	-2%	-12%
Average Condition (%)	-10%	-7%	0%	27%	12%
Average Risk (%)	-24%	-15%	0%	56%	24%
Average Resilience (%)	-10%	-6%	0%	12%	9%
# of intervention actions	28%	23%	0%	-213%	-85%
Time per km per year (hours/km/year)	86%	79%	0%	-206%	2%
Cost per km per year ($//km/year)	7%	5%	0%	-2%	-12%
Average repair length per year (km/year)	13%	12%	0%	-58%	-32%
Average number of interventions per year	28%	23%	0%	-213%	-85%
Ratio of interventions per year - number of annual interventions/number of corridors (%)	33%	17%	0%	-217%	-83%

Table 5-47: *KPIs' summary results for sensitivity analysis – Town of Kindersley*

Performance Indicator	KPI	Weights of importance (%)	Case 1 (-20%)	Case 2 (-10%)	Baseline (Scenario 8)	Case 3 (10%)	Case 4 (20%)
Time	NCR	10%	86%	79%	0%	-206%	2%
Space	STIF	10%	85%	79%	0%	-133%	15%
Cost	LIF	20%	7%	5%	0%	-2%	-12%
Efficiency	IEF	5%	33%	17%	0%	-217%	-83%
Effectiveness	IFF	5%	3%	5%	0%	8%	10%
Condition	CIF	20%	-10%	-7%	0%	27%	12%
Resilience Preparedness	RPIF	10%	-10%	-7%	0%	12%	9%
Risk	RIF	20%	-24%	-15%	0%	56%	24%
Overall deviation (%)			***-3%***	***3%***	***0%***	***7%***	***0%***

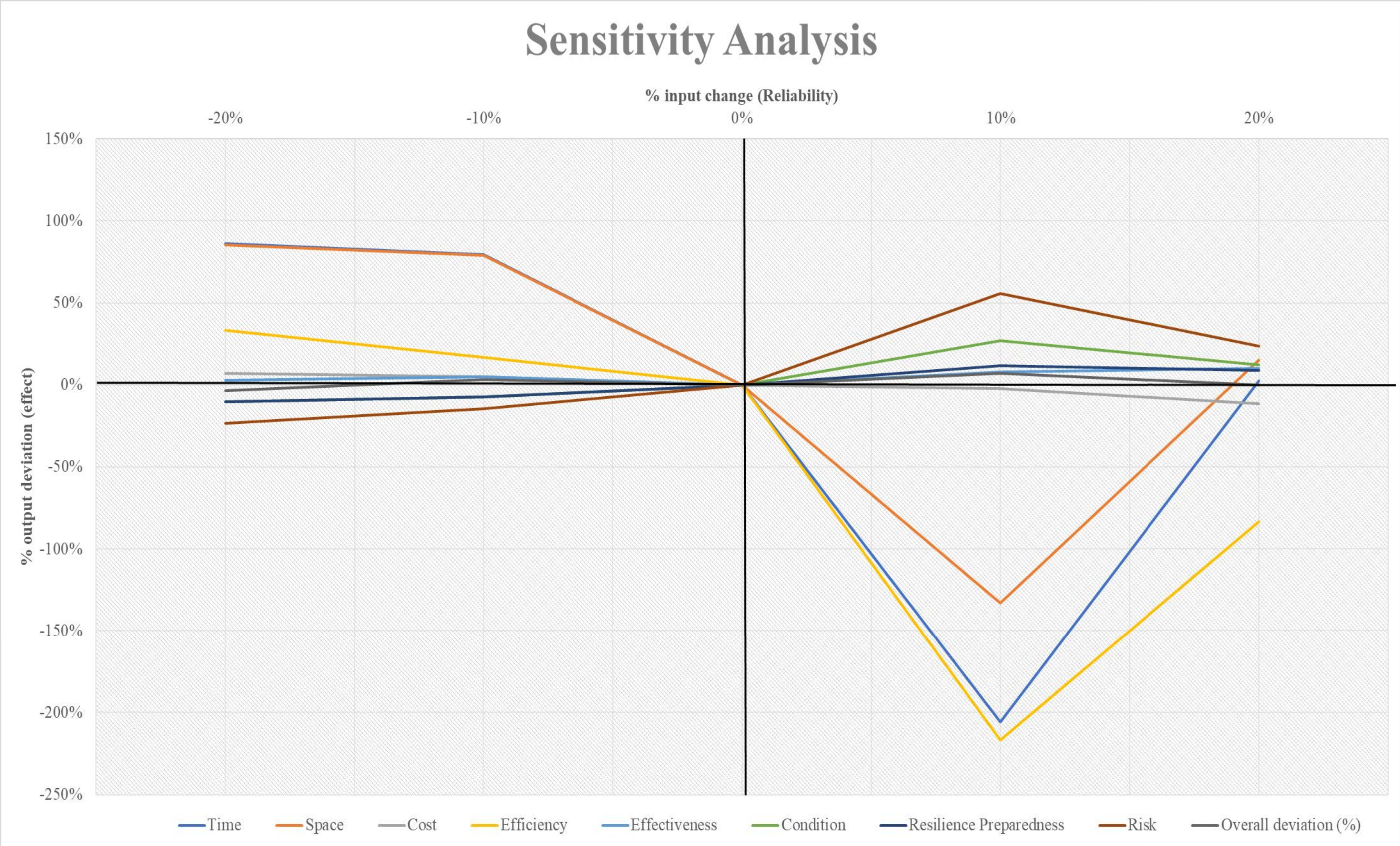


Figure 5.29: *Sensitivity analysis results – Town of Kindersley*

5.3.4 *Model Validation*

Given the fact that the town of Kindersley's data was adopted from a study (Amador and Magnuson 2011), the results should be compared and validated with the study results. However, the comparison was not applicable for the following reasons: (1) the study was applied to the full network of the town of Kindersley but, this study was only limited to 53 km by which the water and sewer pipes are spatially located with a road. Therefore, the scope of work is totally different, and it would be impossible to even exponentially expand the study network given that the average condition of the 53 km might not be representing the average condition of Kindersley network; (2) the study did not consider the intervention planning and coordination (vertical) of the three spatially-located assets (i.e. roads, water, and sewer). It considered horizontal coordination among the corridors such that the intervention actions of the corridors falling in the same area could be combined to reduce the public disruption and reduce the duplicated works (i.e. site preparation, residents' notification, mobilization, and demobilization); and (3) the study did not consider the eight performance assessment indicators. It only considered the LCC and condition. Thus, the other six indicators namely; time, space, risk, resilience preparedness, efficiency, and effectiveness could not be compared and validated with this study. For those reasons, only two out of eight models namely; financial and reliability were statically compared and validated with the study results. To undertake the financial analysis, the intervention actions unit costs were compared with the study's unit costs after applying the time value of money principles. The future unit costs of the study were brought to the present and then the comparison was carried out as outlined in Table **5-48**. The results showed small differences in the road unit costs but large differences in the pipelining and replacement. Those differences were due to the negligence of the pipe material in the study's unit cost. Furthermore, the unit cost estimated in this study includes direct and indirect costs as well as common activities (i.e. site preparation, residents' notification, traffic detours, mobilization, and demobilization, etc.). However, the other study did not include the indirect costs nor the cost of the mobilization and site preparation. For the reliability model validation, the roads' deterioration curves for different road structural designs and traffic categories were adopted from this study and thus, there was no difference between both deterioration curves. Similarly, the water and sewer pipe had negligible difference given that both studies assumed the same service lives for the different pipe materials and diameters.

Table 5-48: *Financial model validation – Town of Kindersley*

System/Asset	Road				Water and sewer pipes				
Intervention actions	Crack sealing ($/m²)	Micro-surfacing ($/m²)	Resurfacing ($/m²)	Reconstruction ($/m²)	Pipelining (Medium-sized pipes) (($/m)	Pipelining (Large-sized pipes) (($/m)	Pipe replacement (Small-sized pipes) (($/m)	Pipe replacement (Medium-sized pipes) (($/m)	Pipe replacement (Large-sized pipes) (($/m)
Uninflated study costs (2011)	$0.33	$6.74	$25.00	$42.00	$500.00	$2,500.00	$210.00	$1,200.00	$4,000.00
Inflated study costs (2017)	$0.38	$7.74	$28.72	$48.24	$574.34	$2,871.71	$241.22	$1,378.42	$4,594.74
System	$0.36	$7.45	$28.00	$46.00	$620.50	$3,121.00	$347.50	$1,747.60	$4,712.87
Difference (Study - System)	$0.02	$0.29	$0.72	$2.24	-$46.16	-$249.29	-$106.28	-$369.18	-$118.13
Difference (%)	5%	4%	2%	5%	-8%	-9%	-44%	-27%	-3%

6 CHAPTER 6 – CONCLUSIONS AND FUTURE DIRECTIONS

This chapter summarizes the research main findings and presents the research contributions to the body of knowledge. Finally, it lists the research limitations and highlights possible directions for future research that are related to the subject matter.

6.1 Summary and Conclusions

Municipalities are experiencing high inefficiency and financial burden imposed by their under-performing infrastructure. Consequently, the risk of sudden failures and service disruptions drastically increases, forcing the municipalities to take immediate corrective actions to maintain the deteriorating assets. Moreover, aging municipal infrastructure systems are placing tremendous pressure on the governments through steeply growing deficits to repair/replace the failing assets. Infrastructure projects typically carry out tons of challenges and risks throughout their service lives due to demand fluctuations, uncertainties, natural disasters occurrence, necessity, and criticality, etc. In such type of projects, crucial intervention decisions are, not only taken at the early beginning of the life-cycle but regularly revised to guarantee the delivery of an acceptable LOS while meeting the tight budgets and upholding with the assets' minimal acceptable condition state. Thus, various alternatives need to be considered to reach the best utilization of the available expenditures and resources while meeting the tight available budgets. The need for asset management adoption has been strengthened by several infrastructure problems (i.e. sudden system failures), as well as the deteriorating LOS, which in return placed tremendous pressure on governments given the urgent need to increase the expenditures to enhance the infrastructure LOS. Urbanization represents another challenge besides the aging infrastructure systems. This, in return, increases the demand on the existing infrastructure (i.e. more traffic on roads, increased demand on processed water, larger sewer pipes, etc.) and forces asset managers to consider resiliency while taking the rehabilitation/replacement decisions (i.e. expand the road and build extra lane, larger water and sewer pipes, build another water pumping station, sewer treatment plant, and water reservoir, etc.).

In the lights of those issues, a comprehensive state-of-the-art review in the areas of asset management, optimization, and PBC was carried out to determine the current practices and accordingly fill the missing gaps. The outcome of this comprehensive review could be summarized as follows: (1) even though plentiful computational models have been developed over the past decade to optimize the expenditures utilization, most of them focused on the development of decision-making frameworks for conventional systems (i.e. roads, water, sewer, bridges, etc.) with less focus on developing a coordinated decision-making framework for the co-located municipal infrastructure; (2) most of the studies failed to consider the propagation of the systems' given the spatial and physical interdependencies among the municipal co-located infrastructure systems; (3) most of the developed asset management frameworks lacked the holistic-based interventions' planning for the co-located infrastructure systems where most scholars independently planned the asset intervention, based on the asset's current condition state, and failed to consider the dimension of time in their decision-making process; (4) there was an absence of an integrated contractual and asset management system that links the KPIs' performance and the P/I application with the decision-making process; (5) few scholars developed dynamic multi-objective optimization models that incorporate the conflicting perspectives and plan the corridor interventions; (6) scholars failed to develop integrated models that aid both municipalities and maintenance contractors in setting up their performance thresholds, P/I system, and maintenance plans; and (7) scholars applied the PBC to roads and transportation projects only, with few applications on the water and sewer rehabilitation projects. In summary, scholars have exerted tremendous efforts on developing decision-support systems on a single-asset level with less focus on integrated asset management in the wider notion of optimization and decision-making.

With an aim to fill in those gaps, this research developed an integrated performance-based multi-objective asset management system for the corridor infrastructure. The framework introduces a novel contractual scheme that advocates integrating the corridor interventions. Furthermore, the system aids the decision-makers in both the pre-contract and post-contract phases. The pre-contract optimization models assist municipalities in defining reasonable KPIs' thresholds as well as P/I systems while designing the PBC. However, the post-contract optimization models assist either municipalities or maintenance contractors in selecting their intervention plans while meeting the limited budgetary constraints. It provides decision-makers with either a near-optimum, using the evolutionary GAs optimization, or exact, using the MOSEK linear programming optimization, coordinated interventions' schedule/plan for the co-located municipal infrastructure. The models are flexible to adapt to different stakeholders' preferences such as; enhanced performance, minimized costs, minimized disruption, etc. The developed coordination framework can be used for intervention scheduling and fund allocation of municipal co-located infrastructure. The research starts by drafting the PBC and defining the KPIs along with their thresholds and associated P/I. Thenceforth, a series of multi-dimensional performance assessment models are developed to quantify the temporal, financial, spatial, risk, reliability, resilience preparedness, efficiency, effectiveness, and health savings indicators for several coordination decisions and compare them with the conventional scenario to compute the potential coordination savings. Those savings are a result of the spatial interdependency among the municipal co-located infrastructure systems. The temporal dimension computes the corridor coordination ratio to compare the conventional intervention scenario output, which rests on the basis of asset-based maintenance, with the fully-coordinated and partially-coordinated outputs, which lies on the basis of coordinating the interventions of the right-of-way assets. The spatial dimension computes the spatial and temporal savings of the fully-coordinated and partially-coordinated coordination scenarios as opposed to the conventional scenario. The financial dimension computes the monetary savings of the fully-coordinated and partially-coordinated coordination scenarios as opposed to the conventional scenario. It incorporates both the direct costs (i.e. manpower, equipment, material) and indirect costs (i.e. disruption – user costs) along with the time value of money while undertaking the trade-off analysis. The intervention efficiency and effectiveness dimensions compute the efficiency and effectiveness of coordinating the intervention actions as opposed to undertaking independent intervention actions for each asset. The efficiency represents the utility cut costs (i.e. longer disruption time) and the effectiveness represents the amount of time when the corridor is disruption-free. The computations are centered on the core of disruption and operating durations. The reliability dimension computes the corridor condition/reliability to reflect the impact of the intervention actions on the corridor condition/reliability for different coordination scenarios. The risk dimension computes the corridor's probability and consequences of failure for the different coordination scenarios. Hence after, it calculates the ratio between the coordinated and conventional intervention scenarios. The resilience preparedness dimension computes the corridor resiliency with respect to climate change and urbanization. It focuses only on the water and sewer pipes' replacement given their long service lives and lengthy public disruptions. It computes the impact of urbanization, represented through land use change and population growth, and climate change, represented through the rainfall intensity and frequency increase, on the water and combined sewer and stormwater systems. The corridor health dimension integrates the scores of the indicators into a health index to assist asset managers in prioritizing the corridors and taking critical intervention decisions. Towards the end, several optimization models were developed for the pre-contract and post-contract phases. The pre-contract optimization provides the municipality with near-optimal KPIs and P/I system that minimizes the maintenance contractors' contingency without compromising the systems' LOS. The post-contract optimization features both a near-optimal hierarchical optimization technique using GAs and an exact optimization technique using MOSEK linear programming optimization engine. The novelty of the multi-objective optimization technique is that it combines metaheuristics, binary coding, integer programming, and non-preemptive goal optimization procedures to trade-off the scheduling of different intervention alternatives, which significantly reduced the search space and allowed the framework to be scaled up either to include more than three infrastructure systems or to extend the planning horizon.

Optimal expenditures utilization is of importance in the decision-making process of infrastructure systems. This system could be used in planning and scheduling the interventions for all the coordination scenarios (i.e. conventional, partially-coordinated, and fully-coordinated). Furthermore, it accounts for the urbanization and climate change effects that, in return, might require some assets to be expanded to meet the increased demand. In summary, this research develops a novel coordination and optimization framework for the municipal co-located infrastructure. The methodology was applied to the roads, water, and sewer networks. However, it can be expanded to include other infrastructure systems that are spatially located with those assets and might require disrupting the traffic such as; oil and gas pipelines, electricity networks, bridges, telecommunication networks, etc. The key resolutions of this system were as follows: (1) quantify and demonstrate the potential coordination savings given the existing spatial interdependency; and (2) integrate the contractual KPIs and P/I system with the decision-making process.

6.2 Research Findings

The system was applied to 9 km from the city of Montréal and expanded to 53 km from the town of Kindersley. The city of Montréal featured a GA-based optimization engine and was modeled using sophisticated spreadsheets integrated with Evolver 7.5. However, the town of

Kindersley was modeled on a professional software package named “REMSOFT” and it featured a linear programming optimization engine named “MOSEK”, which aimed at finding an exact solution for the problem in hand. The results of the two case studies displayed great savings in favor of the full coordination over the conventional asset management (i.e. single asset-based management) in terms of cost, time, space, risk, resilience preparedness, reliability, efficiency, and effectiveness. For the city of Montreal, the pre-contract optimization was able to obtain a near-optimal set of KPIs’ thresholds and their associated penalties and incentives. The post-contract optimization displayed an overall improvement of 15% across 25 years planning horizon as a result of coordinating the interventions compared to the conventional scenario. The 15% improvement was broken down to 12%, 16%, 18%, 30%, 26%, 10%, 10% for the time, space, cost, efficiency, effectiveness, reliability, and risk respectively. In addition, the coordinated intervention program showed to be more efficient in more than 70% of the corridors with fewer interventions for each corridor; more temporal and financial savings; and less public disruption. To analyze the effect of increasing or decreasing the reliability threshold on the other KPIs’, a sensitivity analysis was carried out. The system showed to be very sensitive to changes in the reliability threshold such that increasing the reliability threshold by 10% revealed 42% additional repair time and 31% additional space, 33% extra repair costs for undertaking additional interventions, 13% reduced efficiency given the extra interventions that were undertaken across the planning horizon, 31% less effectiveness with less operating time, 30% increase in the average network reliability and risk, and 12% decrease in the overall improvement.

Similarly, the town of Kindersley post-contract optimization model was run, and the results displayed an overall improvement of 29% across 25 years planning horizon because of coordinating the interventions compared to conventional ones. The 29% improvement was broken down to 72%, 63%, 48%, 67%, 9%, 1%, 14%, and 5% for the time, space, cost, efficiency, effectiveness, reliability, resilience preparedness, and risk respectively. Furthermore, the coordinated intervention program resulted in 67% fewer interventions as opposed to the conventional approach, saving an overall of 374 interventions across the 25 years, equivalent to 15 interventions annually, and drastically reducing the public disruption. To analyze the effect of increasing or decreasing the reliability threshold on the other KPIs’, a sensitivity analysis was developed. The system showed to be very sensitive to changes in the reliability threshold such that decreasing the reliability threshold by 20% revealed 86% less time, 85% less space, 7% less cost, 33% improved efficiency, 3% effectiveness, 10% decline in the average network reliability and resilience preparedness, 24% higher risk because of the declined reliability, and 3% decrease in the overall improvement.

In summary, the system provided the decision-makers with a golden asset management tool that (1) defines the KPIs' thresholds and their associated P/I in the pre-contract phase; (2) optimally allocates the limited budget in the post-contract phase to enhance the performance of the right-of-way corridor assets while minimizing the public disruption and maximizing the intervention program efficiency. The system is flexible to be used for in-house maintenance through setting the financial penalties and incentives to zero "0". Furthermore, the system concluded that there is a need to revisit/increase the municipal budget to close the chronic municipal deficit and rehabilitate/replace the deteriorating assets.

6.3 Research Contributions

The research contributions could be summarized as follows:

1. Undertaking a state-of-the-art review for the current contractual practices and optimization systems in the asset management domain.
2. Designing a novel PBC contractual scheme for the municipal co-located infrastructure systems.
3. Identifying the PBC parameters including the KPIs, their associated thresholds, P/I for the right-of-way assets.
4. Developing temporal, financial, and spatio-temporal savings models to compute the potential coordination savings resulting from integrating the assets' interventions.
5. Developing an integrated deterioration, risk, and resilience preparedness models for computing their improvement for each corridor across the study planning horizon.
6. Developing intervention efficiency and effectiveness models to ensure effective utilization of the expenditures with minimal service disruption and maximum LOS.
7. Developing a prioritization model for ranking the corridors, based on the stakeholders' preferences.
8. Building optimization models for pre-contract and post-contract phases to reasonably define the KPIs' thresholds, P/I, and select a near-optimal (using GAs optimization engine)

or exact (using MOSEK linear programming optimization engine) intervention plan for the municipal co-located infrastructure systems.

6.4 Research Limitations

Despite the capabilities and flexibility of the system, the future work is underway to address some of the limitations that include, but not limited, to the following:

1. Failure to consider more than three infrastructure systems while computing the potential coordination savings.
2. Limiting the study planning horizon to 25 years due to the computational complexity and huge search space associated with the multi-asset nature.
3. Limiting the size of the data set, represented through a smaller number of corridors, resulted in losing the ability to efficiently allocate the budget across large city networks.
4. Failure to account for the detrimental service disruption effect of undertaking coordinated interventions on the same corridor.
5. Failure to quantify the public nuisance impacts for undertaking a coordinated intervention as opposed to the conventional independent interventions.
6. Utilization of deterministic regression deterioration model to predict the future condition of the roads.
7. Lack of operational-based KPIs for each infrastructure system (i.e. road potholes, transverse and longitudinal cracks, crocodile cracks, accident removal, safety consideration, pipe leaks, etc.).
8. Utilization of the same deterioration pattern for the assets after undertaking an intervention (after repair) as opposed to the original (before-repair) one.
9. Absence of a network-level fund allocation model that allocates the budget among different areas, rather than corridors, within the city.
10. Failure to account for operational feasibility while preparing the intervention plan (i.e. ability to mobilize enough maintenance resources in terms of crew (i.e. labor and equipment) in a certain area).
11. Failure to consider the corresponding traffic congestion resulting from the lengthy coordinated systems' disruption.

12. Absence of a resilience preparedness model for the roads network to account for the impact of extreme weather condition (i.e. freeze and thaw) as well as urbanization in terms of early reconstruction or lane expansion possibility.
13. Absence of a comprehensive analysis that studies the applicability of implementing a lane rental approach on the intervention efficiency and effectiveness.
14. Failure to consider other forms of contractual penalties and incentives (i.e. reduction or expansion of the contract duration) other than the financial ones.
15. Failure to account for potential horizontal coordination among the spatially located corridors (i.e. corridors in the same block could be coordinated and maintained in parallel).

6.5 Future Directions

Even though the current research has been able to achieve its objective, there are several recommendations for enhancing or extending this research area for future work. Those recommendations could be categorized into research areas that need enhancement and research areas that need a further extension.

6.5.1 *Enhancement Areas*

The areas that need further enhancement in this research could be summarized as follows:

1. Predicting the condition of roads using regression could be further enhanced using other probabilistic condition prediction models that account for the uncertainties associated with the asset deterioration throughout its life-cycle.
2. Extending the planning horizon to the longest assets' service life.
3. Increasing the size of the data set to incorporate a larger number of corridors, which will extend the search space and accordingly complicate the optimization problem.
4. Estimating the deterioration pattern for the assets after undertaking an intervention (after repair) as opposed to the original (before-repair) one given the fact that the after-repair deterioration pattern is always faster than the original (before repair) one.
5. Considering other forms of contractual penalties and incentives (i.e. reduction or expansion of the contract duration) other than the financial ones.

6.5.2 *Extension Areas*

The areas that need a further extension in this research could be summarized as follows:

1. Incorporating more than three infrastructure systems (i.e. telecommunication network, bridges, oil and gas networks, electricity network, street gutters, storm drain, etc.) in the analysis to maximize the coordination benefits.
2. Incorporating municipal-wide datasets could be attained through using dynamic programming by decomposing the planning horizon into shorter periods of times and running them chronologically until reaching the desired planning horizon.
3. Accounting for the detrimental service disruption effect of undertaking coordinated interventions on the same corridor.
4. Quantifying the public nuisance impacts of undertaking a coordinated intervention as opposed to the conventional independent interventions.
5. Defining operational KPIs for each infrastructure system (i.e. road potholes, transverse and longitudinal cracks, crocodile cracks, accident removal, pipe leaks, etc.).
6. Developing a network-level fund allocation model that allocates the budget among different areas, rather than corridors, within the city.
7. Accounting for operational feasibility while preparing the intervention plan (i.e. ability to mobilize enough maintenance resources in terms of crew (i.e. labor and equipment) in a certain area).
8. Considering the corresponding traffic congestion resulting from the lengthy coordinated systems' disruption.
9. Developing a resilience preparedness model for the roads network to account for the impact of extreme weather condition (i.e. freeze and thaw) as well as urbanization in terms of early reconstruction or lane expansion possibility.
10. Studying the applicability of implementing a lane rental approach on the interventions' efficiency and effectiveness.
11. Considering the potential horizontal coordination among the spatially located corridors (i.e. corridors in the same block). Horizontally coordinating the maintenance of the spatially located corridors will reduce the public disruption and reveal potential temporal and financial savings resulting from the duplicated mobilization and demobilization activities.

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APPENDICES

8.1 Appendix A: Summary of multi-objective optimization literature

Table 8-1: *Summary of research related to single and multi-objective optimization*

Research	Domain of application	Scale of application	Optimization type	Optimization tool	Objective(s)
Abu-Samra *et al.* (2018a)	Roads, water, and sewer	Phased network level	Multi-objective	Integrated goal optimization, dynamic and integer programming, and GAs	Minimize deviations from the budget and performance targets
Abu-Samra and Mokahhal (2018)	Buildings	Project level	N/A	Weighted sum method	Evaluate the building sustainability rating
Abu-Samra *et al.* (2018b)	Roads	Project level	N/A	Multi-Attribute Utility Theory (MAUT) and Analytical Hierarchy Process (AHP)	Predict the condition rating
Ghodoosi *et al.* (2018)	Bridges	Project level	Single objective	GAs	Minimize the equivalent uniform annual cost over the bridge life-cycle
Ismaeel and Zayed (2018)	Water	Network level	Single objective	GAs	Maximize the network performance
Kaddoura *et al.* (2018)	Sewer	Project level	Single objective	MAUT	Prioritize the corridors for rehabilitation based on the aggregated condition index
Salah *et al.* (2018)	Buildings	Project level	Multi-objective	Goal optimization and GAs	Maximize the level of service and minimize the LCC
Abu-Samra (2017a)	Water	Network level	N/A	Benefit/Cost analysis	Select the optimal leak detection coverage scenario over the network
Abu-Samra (2017b)	Buildings	Network level	Single objective	Cash flow analysis and GAs	Select the optimal schedule to minimize the risk impact on the cash flow
Abu-Samra *et al.* (2017a)	Roads, water, and sewer	Network level	Multi-objective	Preemptive goal optimization	Maximize reliability, minimize life-cycle costs, minimize economic losses
Abu-Samra and Ahmed (2017)	Roads and water	Network level	Multi-objective	Non-preemptive goal optimization	Minimize financial, temporal, and condition deviations

Research	Domain of application	Scale of application	Optimization type	Optimization tool	Objective(s)
Abu-Samra *et al.* (2017b)	Roads, water, and sewer	Network level	Multi-objective	Non-preemptive goal optimization	Minimize deviations from annual budget and performance target
Abu-Samra *et al.* (2017c)	Roads	Network level	Multi-objective	Integrated goal optimization and GAs	Minimize deviations from the KPIs' thresholds
Abu-Samra *et al.* (2017d)	Roads	Project level	N/A	MAUT and AHP	Predict the condition rating
Al-Zahab *et al.* (2017)	Water	Network level	Single objective	GAs	Maximize the benefit/cost ratio for prioritizing the leak repairs
Dong and Frangopol (2017)	Bridges	Network level	Single objective	Integrated fragility analysis, latin hypercube sampling, and weibull	Maximize the benefit/cost ratio
El-Masry *et al.* (2017)	Sewer	Network level	N/A	Benefit/Cost analysis	Maximize the benefit/cost ratio
Frangopol *et al.* (2017)	Bridges	Network level	Multi-objective	Integrated probabilistic life-cycle optimisation, MAUT, and risk	Maximize the network performance and minimize the costs
Kim and Frangopol (2017)	Bridges	Network level	Multi-objective	Weighted sum method and GAs with pareto optimization	Minimize the damage detection delay, probability of failure, life-cycle cost, and maximize the service life
Marzouk and Abdel Hamid (2017)	Water	Network level	Single objective	Integrated simo procedure and decision tree	Prioritize the corridors for repair
Mohammed *et al.* (2017)	Roads	Network level	Single objective	GAs	Maximize resilience index
Osman *et al.* (2017)	Water	Network level	Multi-objective	Integrated discrete event simulation and GAs	Minimize the repair time, cost, and pipe break impact
Saad and Hegazy (2017a)	Roads and bridges	Network level	Single objective	Enhanced benefit/cost analysis	Maximize the benefit/cost ratio
Saad and Hegazy (2017b)	Buildings	Network level	Single objective	Microeconomic-based heuristic approach	Maximize the efficiency of expenditure
Saad el al. (2017)	Roads	Network level	Multi-objective	Bi-level goal optimization with pareto (penalty and compromise methods)	Minimize deviations from the pre-defined targets

Research	Domain of application	Scale of application	Optimization type	Optimization tool	Objective(s)
Abu-Samra *et al.* (2016)	Water	Project level	Single objective	Integrated discrete event simulation and GAs	Minimize the risk index represented by consequences of failure and leak severity
Salah *et al.* (2016)	Water	Project level	N/A	AHP decision-making	Select the optimal trenchless technology type
El-Abassy *et al.* (2016)	Water	Project level	N/A	Fuzzy Analytic Network Process (FANP)	Select the optimal trenchless technology type
Al-Anwar *et al.* (2016a)	Roads and bridges	Network level	Multi-objective	Mixed integer-liner programming and pareto optimization	Minimize the network recovery time and public expenditures
Al-Anwar *et al.* (2016b)	Roads and bridges	Network level	Multi-objective	Mixed integer-liner programming and pareto optimization	Minimize the network recovery time and public expenditures
El Chanati *et al.* (2016)	Water	Network level	N/A	FANP ranking	Prioritize the corridors for repair
Hawari *et al.* (2017)	Sewer	Project level	Single objective	Integrated FANP and monte carlo simulation	Prioritize the corridors for rehabilitation
Elsawah *et al.* (2016)	Water and sewer	Network level	Single objective	Ranking method and dynamic weighting system	Prioritize the corridors for repair based on the risk index
Ismaeel and Zayed (2016)	Water	Network level	Single objective	GAs	Maximize the network performance
Kaddoura *et al.* (2016)	Sewer	Project level	Single objective	MAUT	Prioritize the corridors for rehabilitation based on the aggregated condition index
Rashedi and Hegazy (2016a)	Roads, water, and sewer	Network level	Multi-objective	Casual loop diagrams and system dynamics	Maximize performance and minimize costs
Rashedi and Hegazy (2016b)	Buildings	Phased project and network level	Single objective	Mathematical optimization (GAMS/CPLEX) and GAs	Minimize deterioration index
Saad el al. (2016)	Roads	Network level	Multi-objective	Bi-level goal optimization using General Algebraic Modeling System (GAMS)/CPLEX	Minimize deviations from the pre-defined targets
Sabatino *et al.* (2016)	Bridges	Network level	Multi-objective	GAs	Maximize performance, minimize cost and failure consequences

Research	Domain of application	Scale of application	Optimization type	Optimization tool	Objective(s)
Shahata and Zayed (2016)	Roads, water, and sewer	Network level	Single objective	Mixed Delphi and AHP and K-means clustering	Minimize risk index
Abu-Samra (2015)	Roads	Phased project and network level	Multi-objective	Integrated goal optimization and GAs	Minimize deviations from the KPIs' thresholds
CGI (2015)	Roads, water, and sewer	Network level	Multi-objective	Mathematical optimization	Minimize risks and maximize return of investment
Dong *et al.* (2015)	Bridges	Project level	Multi-objective	Integrated benefit/cost analysis, MAUT, and GAs	Maximize the sustainability utility and minimize maintenance cost and failure consequences
El-Hakea and Abu-Samra (2015)	Coastal structures	Project level	Single objective	GAs	Minimize the life-cycle costs
Fathy *et al.* (2015)	Water and sewer	Project level	Single objective	Integrated hierarchical Artificial Neural Network (ANN) and GAs	Minimize the ANN training error to select the best rehabilitation strategy
El-Hakea *et al.* (2015)	Coastal structures	Network level	Single objective	GAs	Minimize the network life-cycle costs
Matar *et al.* (2017)	Water	Project level	Multi-objective	Systems engineering and System of Systems (SoS)	Maximize the project sustainability index
Marzouk *et al.* (2015)	Water	Network level	Single objective	Integrated Geographic Information System (GIS), simo procedure and decision tree	Prioritize the corridors for repair
Osman (2015)	Roads, water, and sewer	Network level	Multi-objective	Non-preemptive goal optimization	Minimize deviations from the pre-defined targets
Ramachandran *et al.* (2015)	Roads and bridges	Network level	Single objective	Nearest neighbor algorithm	Minimize resilience time
Saad and Hegazy (2015a)	Buildings	Network level	Multi-objective	Micro economic-based heuristic	Maximize the benefit per dollar spent
Saad and Hegazy (2015b)	Roads	Network level	Single objective	Loss-aversion	Maximize the gain within the limited budget
Sabatino *et al.* (2015)	Bridges	Project level	Multi-objective	GAs	Maximize the sustainability utility and minimize maintenance cost

Research	Domain of application	Scale of application	Optimization type	Optimization tool	Objective(s)
Tscheikner-Gratl *et al.* (2015)	Roads, water, and sewer	Network level	Multi-objective	Decision tree	Maximize the street priority index
Zdenko *et al.* (2015)	Water	Network level	Single objective	Decision tree	Maximize network performance
Abouhammad and Zayed (2014)	Subway	Network level	Single objective	FANP ranking	Prioritize the repair of the subway stations
Barone and Frangopol (2014)	Bridges	Project level	Multi-objective	GAs	Maximize structural performance and minimize maintenance costs
El-Hakea *et al.* (2014)	Coastal structures	Project level	Single objective	Integrated ANN and GAs	Minimize the training error
Elhadidy *et al.* (2015)	Roads	Network level	Multi-objective	GAs with pareto optimization	Maximize the condition and minimize the cost
Elsawah *et al.* (2014)	Roads, water, and sewer	Network level	Multi-objective	Decision tree	Minimize risk consequences and maximize condition
Farran and Zayed (2015)	Roads, water, and sewer	Network level	Multi-objective	Integrated markov chains and GAs	Minimize life-cycle costs and maximize performance
Hegazy and Saad (2014)	Buildings and roads	Phased project and network level	Single objective	Mathematical optimization	Maximize condition improvement
Khan *et al.* (2014)	Water	Network level	Single objective	Decision tree	Prioritize the corridors for repair
Mostafa and El-Gohary (2014)	Roads and bridges	Network level	Single objective	Decision tree	Maximize benefits
Azeez *et al.* (2013)	Sewer	Network level	Single objective	Fuzzy and simulation-based ranking	Minimize the life-cycle costs
Elsayed and Zayed (2013)	Water	Network level	Single objective	Integrated AHP and MAUT	Prioritize the water main rehabilitation projects
Deco and Frangopol (2013)	Bridges	Network level	Single objective	Integrated fragility analysis, latin hypercube sampling, and weibull	Minimize the network life-cycle risks
Hegazy and Rashedi (2013)	Buildings	Network level	Single objective	GAs clustered segmentation and GAMS/CPLEX	Maximize the network performance

Research	Domain of application	Scale of application	Optimization type	Optimization tool	Objective(s)
Marzouk and Omar (2013)	Sewer	Network level	Multi-objective	GAs	Maximize condition and minimize costs
Mohamed and Zayed (2013)	Water	Network level	Single objective	Integrated MAUT and AHP	Prioritize the corridors for fund allocation
Salman *et al.* (2013)	Water	Network level	Multi-objective	Integrated Unsupervised Neural Networks (UNN) and Mixed Integer Non-Linear Programming (MINLP)	Minimize the repair time and maximize reliability
Sitzabee and Harnly (2013)	Roads	Network level	Multi-objective	Goal optimization	Maximize the priority index
Ward and Savic (2013)	Sewer	Project level	Multi-objective	Integrated AHP and MAUT	Maximize structural condition and minimize costs and risk
Zayed and Mohamed (2013)	Water	Network level	Single objective	Integrated MAUT and AHP	Prioritize the corridors' repair based on the budget priority index
Zhang *et al.* (2013)	Roads	Network level	Single objective	Dynamic programming	Minimize the life-cycle costs
Adey *et al.* (2012)	Roads	Project level	Single objective	Mathematical optimization	Maximize net benefits
Ammar *et al.* (2012)	Water	Network level	Single objective	Integrated Day–Stout–Warren (DSW) algorithm and the vertex method	Minimize the life-cycle costs
Bocchini and Frangopol (2012)	Bridges	Network level	Multi-objective	GAs	Maximize resilience; minimize time and restoration costs
Fares and Zayed (2010)	Water	Network level	N/A	Fuzzy expert system	Rank the corridors based on the risk index
Fares *et al.* (2012)	Roads	Project level	Single objective	GAs	Minimize costs
Farran and Zayed (2012)	Subway	Network level	Single objective	Dynamic markov and GAs	Minimize the life-cycle costs
Hegazy *et al.* (2012)	Roads	Network level	Single objective	Heuristic approach	Minimize the life-cycle costs and prioritize the corridors for repair
Orabi *et al.* (2012)	Roads	Network level	Multi-objective	GAs	Minimize reconstruction costs and network disruption
Osman and Ali (2012)	Roads, water, and sewer	Network level	N/A	System dynamics	Simulate the impacts of policy decisions on the stakeholders' goals

Research	Domain of application	Scale of application	Optimization type	Optimization tool	Objective(s)
Osman *et al.* (2012)	Water and sewer	Phased project and network level	Multi-objective	GAs with pareto optimization	Minimize risk exposure and condition assessment cost
Ali *et al.* (2012b)	Water and sewer	Project and network level	Multi-objective	Integrated markov chains and GAs	Minimize inspection costs
Adey and Hajdin (2011)	Bridges	Project level	N/A	Benefit/Cost analysis	Maximize benefit/cost ratio
Amador and Magnuson (2011)	Roads, water, and sewer	Network level	Multi-objective	Integrated classical time-space adjacency modelling, heuristic simulation, and mathematical optimization	Minimize the life-cycle costs and service disruption
Atef *et al.* (2011)	Water and sewer	Network level	Multi-objective	Integrated markov chains and GAs	Maximize condition and minimize costs
De la Garza *et al.* (2011)	Roads	Network level	Single objective	Mathematical optimization	Maximize network performance
Hegazy and Elhakeem (2011)	Buildings	Phased project and network level	Single objective	GAs	Maximize benefit/cost ratio
Shahata and Zayed (2011)	Water	Project level	Single objective	Simulation-based life-cycle costs and decision tree	Minimize the life-cycle costs
Shehab-El-deen and Moselhi (2011)	Sewer	Network level	Multi-objective	MAUT	Minimize the cost and time
Ammar *et al.* (2010)	Water	Network level	Single objective	Integrated DSW algorithm and fuzzy set theory	Minimize the life-cycle costs
Atef *et al.* (2010)	Water and sewer	Network level	Multi-objective	Partially observable markov decision process	Minimize the cost and maximize the reliability
Moselhi *et al.* (2010)	Water	Network level	Single objective	AHP decision-making	Maximize the level of service within the available budget
Okasha and Frangopol (2010)	Bridges	Project level	Multi-objective	GAs	Minimize dysfunctionality, maximize redundancy, and minimize life-cycle costs
Shahata and Zayed (2010)	Roads, water, and sewer	Network level	Single objective	GAs	Minimize repair costs

Research	Domain of application	Scale of application	Optimization type	Optimization tool	Objective(s)
Zhao *et al.* (2010)	Buildings	Network level	Multi-objective	Geometrical pareto selection and double neighbored crossover	Maximize the network performance and minimize the costs
Alvisi and Franchini (2009)	Water	Network level	Multi-objective	GAs with pareto optimization	Minimize repair costs and water losses
El-behairy *et al.* (2009)	Bridges	Network level	Single objective	Sequential optimization	Maximize the network performance
Farran and Zayed (2009)	Subway	Network level	N/A	Dynamic markov chain	Rank the stations for repair
Liu and Frangopol (2009)	Bridges	Network level	Multi-objective	GAs	Maximize the network reliability and minimize the life-cycle costs
Mavrotas (2009)	Buildings	Project level	Multi-objective	E-Constraint Method using lexicographic/preemptive procedure	Minimize the total cost, maximize the level of service, maximize profit
Orabi *et al.* (2009)	Roads	Project level	Multi-objective	GAs	Minimize reconstruction costs
Shahata and Zayed (2009)	Water	Network level	Single objective	Monte carlo simulation	Minimize the life-cycle costs
Scheinberg and Anastasopoulos (2009)	Roads	Phased project and network level	Multi-objective	Mathematical optimization and mixed integer programming	Minimize costs and maximize condition
Al-Barqawi and Zayed (2008)	Water	Project level	N/A	Integrated AHP and ANN	Prioritize the corridors for repair
Dridi *et al.* (2008)	Water	Network level	Single objective	GAs	Minimize the life-cycle costs
Muschallah (2008)	Sewer	Network level	Multi-objective	GAs with pareto optimization	Maximize condition and minimize costs
Wu and Flintsh (2008)	Roads	Project level	Multi-objective	GAs	Maximize the level of service and minimize the preservation costs
Alvisi and Franchini (2007)	Water	Network level	Multi-objective	GAs	Minimize cost and maximize performance
Frangopol and Liu (2007)	Bridges	Network level	Multi-objective	GAs	Maximize condition and safety and minimize life-cycle costs

Research	Domain of application	Scale of application	Optimization type	Optimization tool	Objective(s)
Guistolisi *et al.* (2006)	Water	Network level	Multi-objective	Benefit/Cost analysis	Maximize benefit/cost ratio
Karlafits *et al.* (2007)	Bridges	Network level	Single objective	GAs	Maximize level of service
Al-Barqawi and Zayed (2006a)	Water	Network level	Single objective	Integrated AHP and ANN	Maximize the network performance
Chootinan *et al.* (2006)	Roads	Project level	Single objective	Stochastic simulation and GAs	Maximize the level of service
El-behairy *et al.* (2006)	Bridges	Network level	Single objective	GAs and Shuffled Frog Leaping (SFL)	Minimize the life-cycle costs
Hegazy (2006)	Bridges	Network level	Single objective	GAs	Minimize the life-cycle costs
Elbeltagi *et al.* (2005b)	Bridges	Network level	Multi-objective	GAs, memetic algorithms, particle swarm, ant colony systems, and SFL	Maximize performance and efficiency and minimize time, resources, and cost
Elhakeem and Hegazy (2005)	Roads, water, and sewer	Network level	Single objective	Nomographs	Minimize the cost to allocate the manpower resources
Hegazy (2005)	Roads	Network level	Single objective	GAs	Minimize the life-cycle costs
Liu and Frangopol (2005)	Bridges	Network level	Multi-objective	Event tree analysis and GAs	Minimize the net present value of the maintenance costs and maximize the network performance
Morcous and Lounis (2005)	Bridges	Network level	Single objective	Markov chains and GAs	Minimize the life-cycle costs
Osman (2005)	Roads, water, and sewer	Network level	Multi-objective	Monte carlo simulation	Minimize risks and maximize return of investment
Abaza *et al.* (2004)	Roads	Network level	Single objective	Markovian non-linear programming	Maximize the network condition within the budget
Dicdican *et al.* (2004)	Roads and bridges	Network level	Multi-objective	GAs	Minimize short and long-term costs and maximize service life

Research	Domain of application	Scale of application	Optimization type	Optimization tool	Objective(s)
Hegazy *et al.* (2004a)	Bridges	Phased project and network level	Multi-objective	GAs	Maximize the performance and minimize the cost
Hegazy *et al.* (2004b)	Roads	Network level	Single objective	GAs	Maximize the network performance
Hegazy *et al.* (2003)	Buildings	Network level	Single objective	GAs	Minimize the costs with optimal resource allocation
Halfawy *et al.* (2002)	Roads, water, and sewer	Network level	Multi-objective	Integrated GIS and mathematical optimization	Minimize cost and maximize condition
Tong *et al.* (2001)	Buildings	Network level	Single objective	GAs	Minimize replacement costs
Fwa *et al.* (2000)	Roads	Project level	Multi-objective	GAs	Minimize maintenance costs, maximize condition and maintenance efficiency
Miyamoto *et al.* (2000)	Bridges	Project level	Single objective	GAs with ε-constraint method	Maximize performance (capability and durability)
Liu and Wang (1996)	Roads	Network level	Single objective	Linear programming	Maximize the network performance
Hegazy *et al.* (1994)	Roads	Network level	Multi-objective	Enhanced backpropagation for neural networks using heuristics	Maximize the network performance

8.2 Appendix B: City of Montréal Case Study

The physical and financial related data (i.e. physical state, operation and maintenance costs, water and sewer pipe breaks, etc.) was extracted from two sources: (1) interviews with city officials (Hachey 2017; Sabourin 2017); and (2) city of Montréal official website (Ville de Montréal 2017a; Ville de Montréal 2017b). The dataset was split into three categories for all the n_s systems. Each category comprises physical and financial data. Furthermore, Montréal's indicators were compared with other cities to display the performance difference and its' impact on the assets' physical and financial performance.

8.2.1 *Roads Network*

8.2.1.1 *Physical State*

A sample from the physical state data for each section in Montréal road network could be displayed in Table 8-2 and Table 8-3. The data included the street name, length, inspection data, PCI, condition state, International Roughness Index (IRI), LOS state. The displayed tables are in French and were translated prior to being used in the system. Furthermore, a sample from the GIS map could be displayed in Figure 8.1. To get the global picture, the percentage of paved roads in good or very good condition state was used. This indicator measures the percentage of kilometers of paved roads, which are rated 'good' to 'very good' or whose renewal needs are not estimated necessary before five years. The methodology is based on two factors: the annual average daily flow and the maximum speed. The considered pavements are the ones whose surface is coated with asphalt bituminous or concrete. The road network of the city is characterized by a great diversity of use. The volume and intensity of traffic vary according to their use (i.e. local, main, arterial). However, there is an increased need for maintenance due to the declining condition state, as shown in Figure 8.2 and Table **8-4**. In addition, Montréal roads are worse than other municipalities due to the extreme climatic condition, which speeds up the deterioration of road infrastructure (i.e. freeze and thaw cycles), as displayed in Figure 4.3. Cycles of freezing and thawing, observed mainly in the spring, favor the appearance of potholes, resulting in significant resurfacing costs among others. In addition, a large portion of the roads had their foundations built in the 1960s and have reached the end of their service lives and thus, the degradation rate of the surface coating is accelerating over time. The mathematical formulation of the indicator is shown in Equation 8.1. Details about the variables could be displayed in Figure **8.4**.

$$\% \text{ of kilometers in good or very good condition} = \frac{\text{Number of kilometers in good to very good condition}}{\text{Number of kilometers of paved path}} \tag{8.1}$$

The percentage of roads in good or very good condition was 29.49% in 2016, representing an increase of 2.4% from 2015. Given the massive investment planned by the city of Montréal in the next 10 to 20 years for the roads rehabilitation, the rate is expected to improve gradually in the coming years. Furthermore, a new condition assessment strategy is currently deployed to ensure frequent updates for the roads' condition states, such that the arterial streets will be checked on a two-year period, whereas local streets will be checked on a four-year cycle. On the cities comparison, Montréal revealed lower results than the median of the selected cities, for the third year in a row, with an average drop of 40%. With 29.49% of the road network in good to very good condition states, the city is located at the bottom of the list. Those results reflect the lack of maintenance in the road infrastructure that has persisted for years. The gap is likely to reverse in the future due to the increased investment.

Numerous factors influence the deterioration of the roads infrastructure such as; (1) economic conditions, where the variety of amount of asphalt or concrete pavements as well as the dependence on contractual services can help reduce the maintenance for a given budget; (2) maintenance standards, where the existence of different standards, adopted by the respective municipal councils, can have an impact on the costs and the quality of the roads; (3) traffic and urban conditions, where traffic can accelerate the deterioration of roads and increase the frequency as well as the cost of maintenance of the latter. Congestion, narrowness of the streets, the additional presence of traffic lights, and the maintenance performed at unconventional hours can also lead to an increase in the costs; and (4) climatic conditions, where the frequency and the severity of certain weather conditions have an impact on the operation and maintenance costs, as well as the thresholds of response and service standards adopted by each municipality.

Table 8-2: *Sample from the road CCS and LOS (1 out of 2) (Ville de Montréal 2017a)*

Grid | Graph | Map | 1000 records | « 201 – 300 » | Search data ... | Go » | Filters

ID_TRC	Rue	De	A	Longueur	Arrondi…	DateRel…	Indice PCI	Etat PCI	Indice IRI	Etat IRI
1010400	Lachapel…	rue Prina…	rue Legault	159	Ahuntsic…	2015-07-…	61	Moyen	3.65	Moyen
1010401	Lachapel…	rue Legault	rue Ranger	105	Ahuntsic…	2015-07-…	55	Mauvais	3.96	Moyen
1010403	Lachapel…	rue mile-…	rue De…	83	Ahuntsic…	2015-07-…	62	Moyen	4.1	Moyen
1010404	Lachapel…	rue De…	rue Chev…	198	Ahuntsic…	2015-07-…	71	Moyen	2.89	Moyen
1010405	Lachapel…	rue Chev…	boulevar…	69	Ahuntsic…	2015-07-…	52	Mauvais	4.97	Mauvais
1010406	Lachapel…	boulevar…	rue du B…	128	Ahuntsic…	2015-07-…	47	Mauvais	4.21	Moyen
1010407	Lachapel…	rue du B…	rue du B…	40	Ahuntsic…	2015-07-…	66	Moyen	2.32	Bon
1010408	Lachapel…	rue du B…	rue de L'…	112	Ahuntsic…	2015-07-…	65	Moyen	3.32	Moyen
1010409	De Lamo…	rue De T…	rue De…	261	Ahuntsic…	2015-07-…	59	Moyen	3.32	Bon
1010413	Laurenti…	boulevar…	rue De P…	79	Ahuntsic…	2015-07-…	20	Trs mau…	6.04	Trs mau…
1010415	Laurenti…	rue De P…	rue De S…	39	Ahuntsic…	2015-07-…	74	Moyen	7.86	Trs mau…
1010416	Laurenti…	rue De S…	rue Prina…	132	Ahuntsic…	2015-07-…	85	Bon	4.45	Moyen
1010417	Laurenti…	rue Prina…	rue mile-…	173	Ahuntsic…	2015-07-…	74	Moyen	3.26	Moyen
1010419	Laurenti…	rue mile-…	boulevar…	87	Ahuntsic…	2015-07-…	91	Excellent	3	Moyen
1010420	Laurenti…	boulevar…	rue Vanier	108	Ahuntsic…	2015-07-…	41	Mauvais	3.68	Moyen
1010421	Laurenti…	rue Vanier	rue du B…	65	Ahuntsic…	2015-07-…	44	Mauvais	3.06	Moyen
1010422	Laurenti…	rue du B…	pont Lac…	74	Ahuntsic…	2015-07-…	32	Trs mau…	3.93	Moyen
1010424	Laurin rue	rue Cous…	chemin d…	107	Ahuntsic…	2015-07-…	46	Moyen	3.78	Bon
1010425	Lavigne…	rue Lavi…	rue Dud…	224	Ahuntsic…	2015-07-…	39	Mauvais	5.29	Moyen
1010426	Lavigne…	rue Dud…	rue de L…	324	Ahuntsic…	2015-07-…	47	Moyen	4.17	Moyen
1010427	Lavigne…	rue de L…	rue De S…	323	Ahuntsic…	2015-07-…	32	Mauvais	5.66	Moyen
1010428	Lavigne…	rue De S…	rue Forbes	302	Ahuntsic…	2015-07-…	47	Moyen	4.27	Moyen
1010429	Lavigne…	rue Jules…	boulevar…	206	Ahuntsic…	2015-07-…	43	Moyen	5.21	Moyen

Table 8-3: *Sample from the road CCS and LOS (2 out of 2) (Ville de Montréal 2017a)*

Grid | Graph | Map | 1000 records | « 1 – 100 » | Search data ... | Go » | Filters

ID_TRC	Rue	De	A	Longueur	Arrondi…	DateRele…	Indice PCI	Etat PCI	Indice IRI	Etat IRI
1030169	Fleury E…	Grande…	rue Lave…	91	Ahuntsic…	2011-06-14	26	Trs mau…	5.26	Moyen
1030199	Gouin E…	Grande…	rue Lave…	91	Ahuntsic…	2011-06-22	56	Mauvais	5.01	Mauvais
1030247	Henri-Bo…	Grande…	rue Lave…	90	Ahuntsic…	2010-11-18	91	Excellent	2.75	Moyen
1030410	Prieur E…	Grande…	rue Lave…	90	Ahuntsic…	2011-06-09	44	Moyen	4.99	Moyen
1030375	Meunier…	alle Sauriol	rue Fleur…	259	Ahuntsic…	2011-06-28	40	Mauvais	4.84	Moyen
1010589	De Sala…	autorout…	rue Marsan	119	Ahuntsic…	2010-10-28	66	Moyen	3.44	Moyen
1010272	Gouin O…	avenue…	avenue…	81	Ahuntsic…	2010-10-28	100	Excellent	3.48	Moyen
1010539	Paul-Mor…	avenue…	avenue…	63	Ahuntsic…	2011-06-17	78	Bon	3.84	Bon
1010661	Toupin b…	avenue…	rue de B…	52	Ahuntsic…	2011-06-17	71	Bon	4.05	Moyen
1010268	Gouin O…	avenue…	avenue J…	157	Ahuntsic…	2010-10-28	81	Bon	4.94	Mauvais
1010357	Jean-Bo…	avenue…	avenue…	80	Ahuntsic…	2011-06-17	47	Moyen	8.56	Trs mau…
1010444	Lon-Trpa…	avenue…	rue Jasmin	59	Ahuntsic…	2011-06-22	54	Moyen	3.35	Bon
1010456	Louis-Ja…	avenue…	rue Mtivier	42	Ahuntsic…	2011-06-22	61	Bon	3.65	Bon
1020046	Alexandr…	avenue…	rue de L…	248	Ahuntsic…	2011-06-28	88	Excellent	2.51	Bon
1020327	Frigon rue	avenue…	rue Char…	304	Ahuntsic…	2011-06-14	42	Moyen	7.52	Mauvais
1020394	James-…	avenue…	avenue…	53	Ahuntsic…	2011-06-27	37	Mauvais	5.13	Moyen
1020416	Joseph-…	avenue…	place Jo…	85	Ahuntsic…	2011-06-28	62	Bon	5.95	Moyen
1020587	Pasteur r…	avenue…	avenue…	88	Ahuntsic…	2011-06-28	73	Bon	3.65	Bon
1020638	De Poutr…	avenue…	rue Dud…	23	Ahuntsic…	2011-06-28	67	Bon	8.36	Trs mau…
1020717	de l'Aca…	avenue…	rue Lavi…	158	Ahuntsic…	2011-06-28	69	Bon	3.08	Bon
1010271	Gouin O…	avenue…	avenue…	82	Ahuntsic…	2010-10-28	93	Excellent	3.49	Moyen
1010360	Jean-Bo…	avenue…	avenue…	127	Ahuntsic…	2011-06-17	46	Moyen	7.1	Mauvais

where ID_TRC is the ID of the corridor according to the geobase (digital); Rue is the street name (variable text); De is the beginning street name (variable text); A is the ending street name (variable text); Longueur is the length of the corridor (m); Arrondissement is the borough/area it belongs to (variable text); Date Releve is the date of the last road surface inspection that represents those results (date and/or time); Indice PCI is the pavement condition index indicator that represents the surface condition (0-100); Etat PCI is an interpretation of the PCI index (excellent, bon, moyen, mauvais, and tres mauvais); Indice IRI is the international roughness index indicator that represents the LOS (0-10); and Etat IRI is an interpretation of the IRI index (excellent, bon, moyen, mauvais, and tres mauvais).

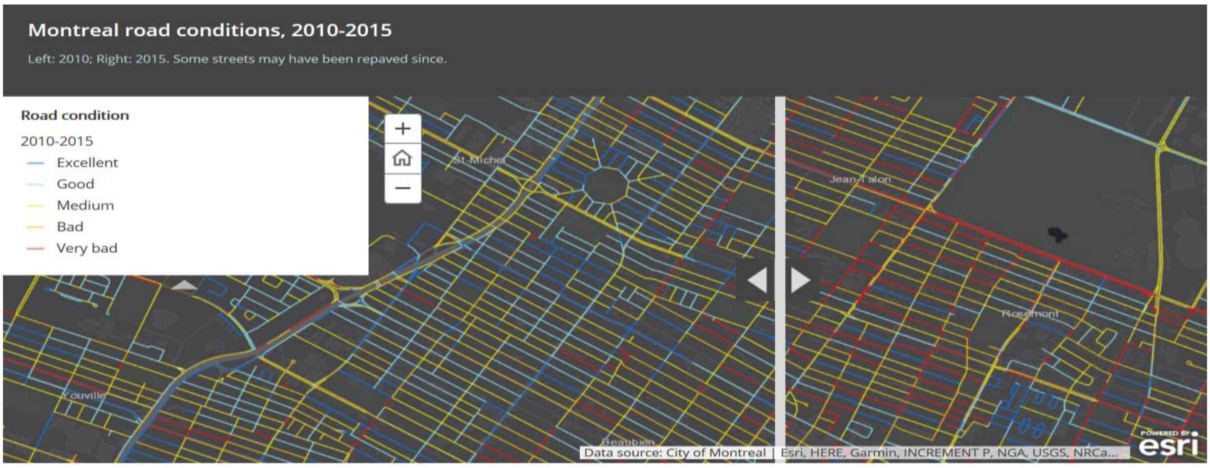


Figure 8.1: *GIS sample from the city of Montréal road network (Ville de Montréal 2017a)*

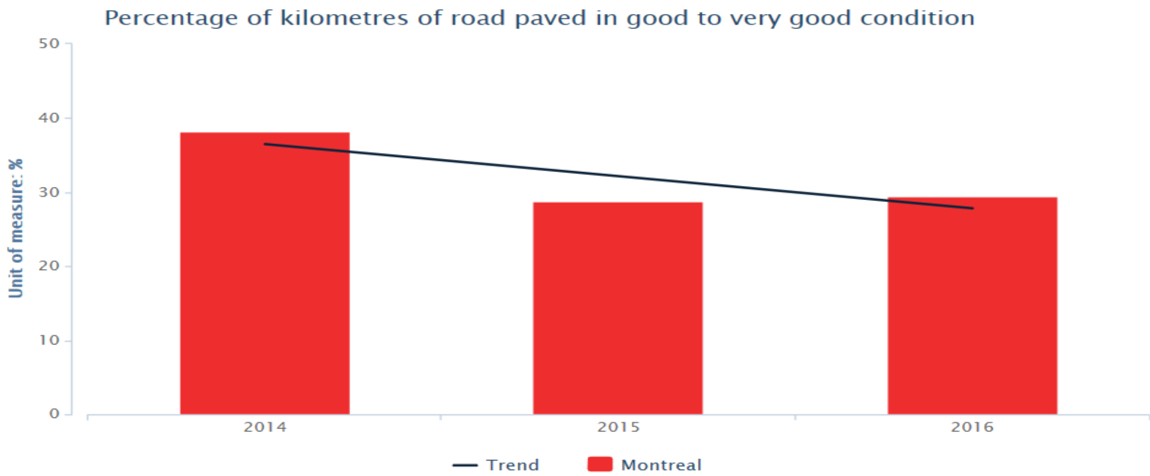


Figure 8.2: *Percentage of roads in good and very good condition states (Ville de Montréal 2017b)*

Table 8-4: *Analytical table for the percentage of roads in good and very good condition states (Ville de Montréal 2017b)*

	2014	2015	2016
Number of kilometres of road paved in good to very good condition	4 411	3 317	3 341
Number of kilometres of paved path	11 560	11 520	11 329
Percentage of kilometres of road paved in good to very good condition	38,16	28,79	29.49
Gap with previous year	-	-24,6%	2.4%
Evolution			-22,7%

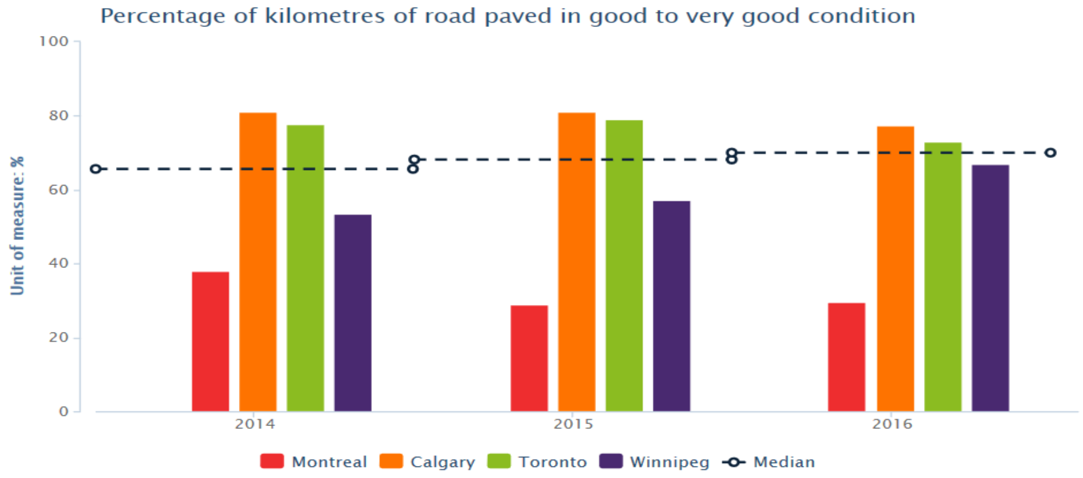


Figure 8.3: *Comparison of the percentage of roads in good and very good condition states among Canadian cities (Ville de Montréal 2017b)*

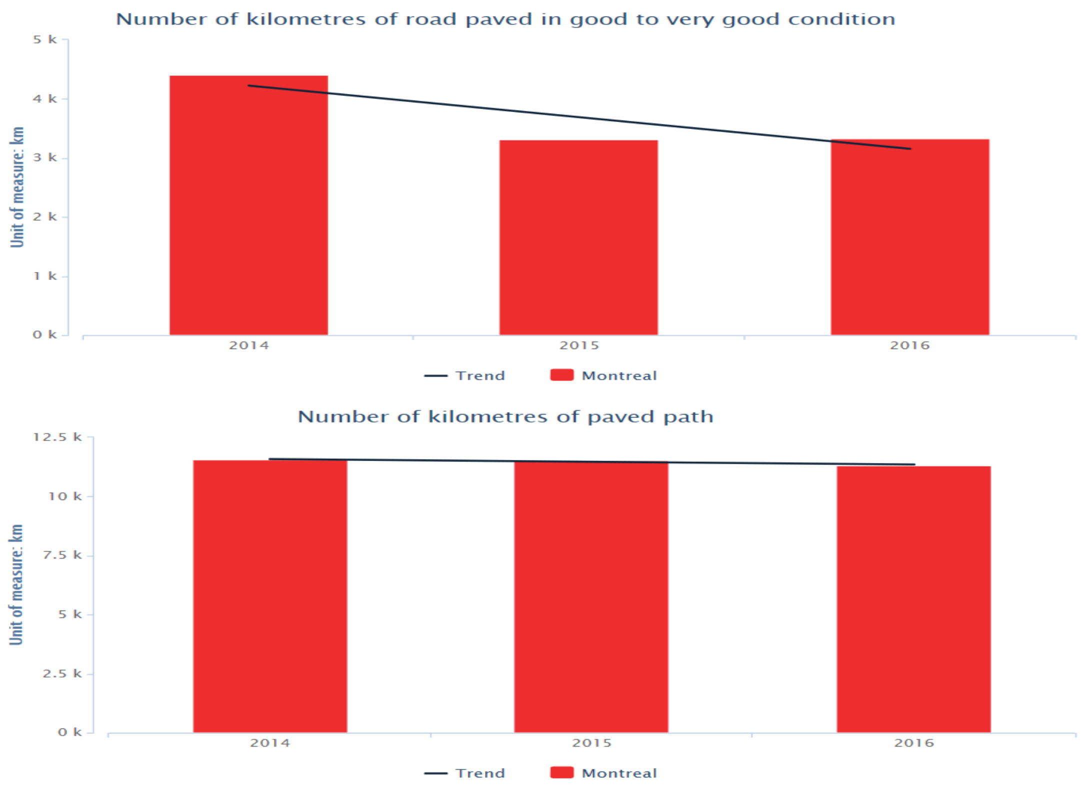


Figure 8.4: *Variables analysis for the percentage of roads in good and very good condition states indicator (Ville de Montréal 2017b)*

8.2.1.2 *Financial*

The financial data was represented through two indicators: (1) total costs of the paved roads per kilometer; and (2) cost of municipal roads per lane-kilometer. The 1st indicator mainly considers all the direct and indirect costs including but not limited to potholes repair, cracks sealing, minor repairs, major rehabilitation, streets cleaning, and related administrative costs. However, it excluded the costs related to traffic management and winter maintenance activities (i.e. snow removal). The total cost includes depreciation and the support costs such as; flagman. Moreover, it includes the indirect institutional expenditures such as; budget management, accounting, management of human resources, purchasing, inventory management, information technology, legal services, etc. The road network of the city is characterized by a great diversity of use. The volume and intensity of traffic vary according to their use (i.e. local, main, arterial). In addition, Montréal roads are worse than other municipalities due to the extreme climatic condition, which speeds up the deterioration of the roads' infrastructure (i.e. freeze and thaw cycles). Those cycles of freezing and thawing, observed mainly in the spring, favor the appearance of potholes, resulting in significant resurfacing costs among others. In Quebec, the responsibility of these pathways is mixed, where it is shared between the municipal and provincial governments.

On the financial side, Montréal is faced with the challenge of reducing its maintenance deficit while maintaining a safe and acceptable level for the paved roads. Given the state of obsolescence of its infrastructures, the city decided to massively speed up its investment in the rehabilitation of these assets in the next 10 to 20 years, which is reflected in the total cost per kilometer of paved path, as shown in Figure 8.5. The cost jumped by 6.7% from \$24k in 2014 to \$25.5k in 2015 and 7.2% in 2016 to \$27.5k, as displayed in Table **8-5**. This growth is primarily related to an increase in operating costs with about 7% (\$6.5M) and an increase in amortization expense with about 6.5% (\$9.7M). The overall increase was estimated at 14% between 2014 and 2016, due to the increase in operating costs associated with the need for regular streets interventions. Similarly, Figure 8.6 and Table **8-6** displayed the same pattern for the costs without amortization/depreciation. The mathematical formulation of the costs could be displayed in Equation 8.2. Details about the variables could be displayed in Figure 8.9.

$$\text{Total costs of the paved roads per kilometer} = \left(\frac{\textit{Direct costs the cobblestone lane} + \textit{Support costs to activities related to the cobbled lanes} + \textit{Depreciation relative to the cobbled lanes}}{\textit{Number of kilometers of paved path}}\right) \tag{8.2}$$

For the third year in a row, Montréal displayed the highest cost per kilometer among the cities where the average cost increase was estimated at 153.9% as opposed to the median, as displayed in Figure 8.7 and Figure **8.8**. As highlighted previously, this cost reflects the city's efforts to deal with the maintenance deficit of its road infrastructure. Amortization expense, which is a reflection of the investment extent to the restoration or reconstruction of roads, was estimated at $159.2M in 2016, which is $14,054 more than the total cost per kilometer, as displayed in Figure 8.7 and Figure **8.8**. In addition to the level of investment, the depreciation policy may also partially explain the observed differences among the cities. In Montreal, the amortization period is between 10 and 40 years. However, the amortization period of the roads in Toronto is between 25 and 70 years according to the city's 2015 financial report. These differences between depreciation policies have a significant impact on the results. Similarly, Figure **8.8** displayed the same pattern for the comparison results without amortization/depreciation.

Numerous factors influence the total costs of the paved roads per kilometer such as; (1) capitalization and amortization policy, where expenditure capitalization thresholds and depreciation rates differ according to the municipalities (i.e. an activity could be considered as part of the operating budget in one municipality, whereas in another municipality, it could be capitalized); (2) economic conditions, where the variety of the asphalt or concrete pavements as well as the dependence on contractual services can help reduce the maintenance for a given budget; (3) maintenance standards, where the existence of different standards, adopted by the respective municipal councils, can have an impact on the costs and the quality of the roads; (4) traffic and urban conditions, where traffic can accelerate the deterioration of roads and increase the frequency as well as the cost of maintenance of the latter. Congestion, narrowness of the streets, the additional presence of traffic lights, and the maintenance performed at unconventional hours can also lead to an increase in costs; (5) climatic conditions, where the rainfall frequency and severity/intensity have an impact on the costs of operation and maintenance, as well as the thresholds of response and service standards adopted by each municipality; and (6) infrastructure repair, where the repair cost can significantly vary from one year to another according to the network condition state and the number of corridors that require repair/rehabilitation.

The 2nd indicator considers the costs associated with the operations, maintenance, and rehabilitation of pavements and sidewalks, as well as cleaning and sweeping of public roads. The cost of municipal roads per lane-kilometer consists of operating and depreciation expenses minus the services rendered. It also includes the indirect costs of the administrative and technical support that represent the indirect institutional expenditures such as; budget management, accounting, management of human resources, purchasing, inventory management, information technology, legal services, etc. It covers all the arterial roads as well as the secondary network of Montréal's 19 boroughs. However, it excludes the secondary roads of the newly constructed areas. It should be noted that the lanes differ according to the usage and areas. For instance, a lane can be reserved for buses and taxis in the peak period and dedicated to parking the rest of the day. It is obvious that the relative cost of municipal roads per lane-kilometer increased by 8% from 2015 to 2016; where it was estimated at \$28.9k in 2015 and jumped to \$31.2k in 2016, as displayed in Figure 8.10 and Table **8-7**. This jump is a result of the increase in the cost of municipal road interventions and the amortization expenses. The increase in the cost of municipal road interventions is linked to the dire need for regular maintenance and rehabilitation, given the high percentage of dysfunctional roads. The maintenance cost increased by 6.8%, which represents \$9M, from 2015 to 2016. Similarly, the amortization expense increased by 5.6%, which represents \$11.4M, in 2016 as opposed to 2015. The overall increase in the cost of municipal roads per lane-kilometer was estimated at 18.4% mainly due to the amortization expenses which jumped by 21.3% from \$178.6M in 2012 to \$216.6M in 2016. This is well-aligned with the city's plan to continue investing in the infrastructure rehabilitation over the next 10 to 20 years. Furthermore, the cost of the municipal road interventions increased by 9.1% from \$129.5M in 2012 to \$141.3M in 2016, where the potholes filling, estimated at 2,000 potholes per day, as well as roads cleaning and sweeping are the two main contributors to that increase. Numerous factors influence the cost of municipal roads per lane-kilometer such as; maintenance equipment condition, maintenance frequency, etc. The mathematical formulation of the costs could be displayed in Equation 8.3. Details about the variables could be displayed in Figure 8.11.

$$\text{Cost of municipal roads per lane} - \text{kilometer} = \left(\frac{\textit{Cost of municipal roads interventions} - \textit{Services of municipal highways} + \textit{Road depreciation}}{\textit{Number of kilometers of roads}}\right) \tag{8.3}$$

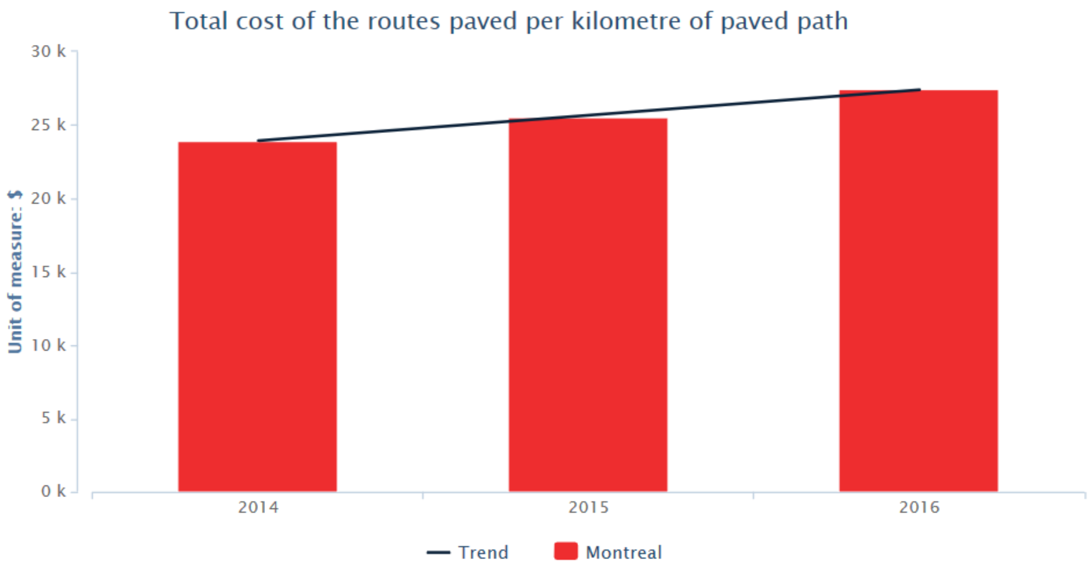


Figure 8.5: *Total cost of the roads' maintenance per kilometer (Ville de Montréal 2017b)*

Table 8-5: *Analytical table for the total cost of the roads' maintenance per kilometer (Ville de Montréal 2017b)*

	2014	2015	2016
Direct costs the cobblestone lane	105 109 177	109 291 566	115 803 956
The support activities costs the cobblestone lane	29 569 943	35 891 339	35 922 986
Depreciation relative to the cobbled lanes	142 510 499	149 553 075	159 221 711
Number of kilometres of paved path	11 560	11 520	11 329
Total cost of the routes paved per kilometre of paved path	23 978	25 585	27 447
Gap with previous year	-	6.7%	7.3%
Evolution			14.5%

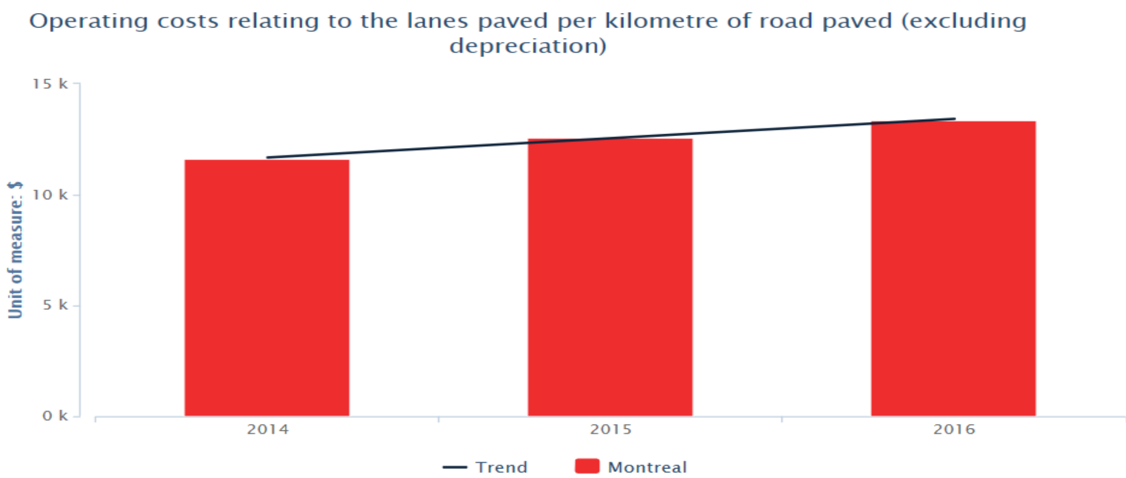


Figure 8.6: *Total cost of the roads' maintenance per kilometer (excluding depreciation) (Ville de Montréal 2017b)*

Table 8-6: *Analytical table for the total cost of the roads' maintenance per kilometer (excluding depreciation) (Ville de Montréal 2017b)*

	2014	2015	2016
Operating costs the way paved by Lane-kilometre paved (excluding amortization)	11 650	12 603	13 393
Gap with previous year	-	8.2%	6.3%
Evolution			15.0%

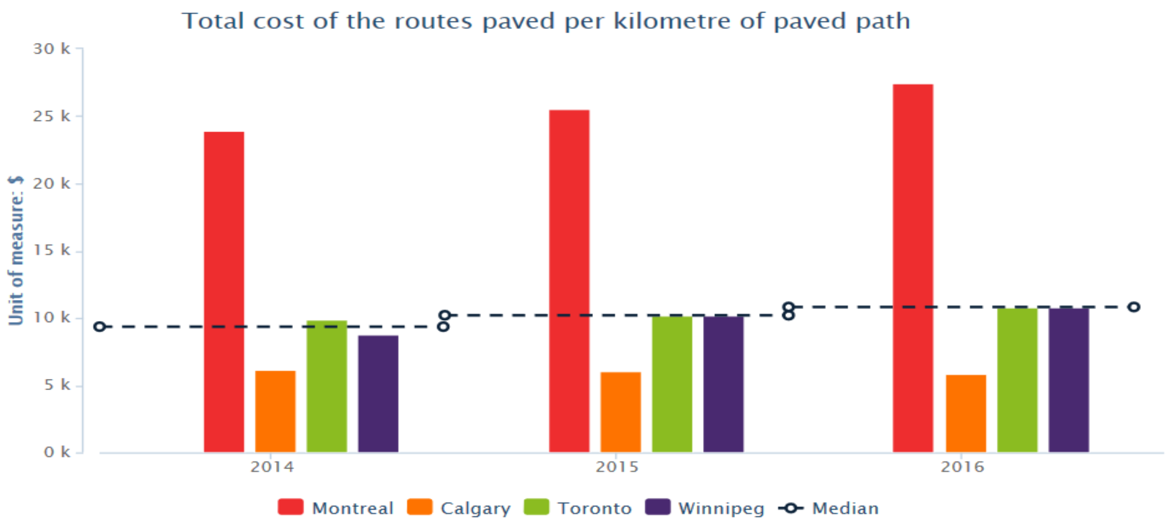


Figure 8.7: *Comparison of the total cost of the roads' maintenance per kilometer among Canadian cities (Ville de Montréal 2017b)*

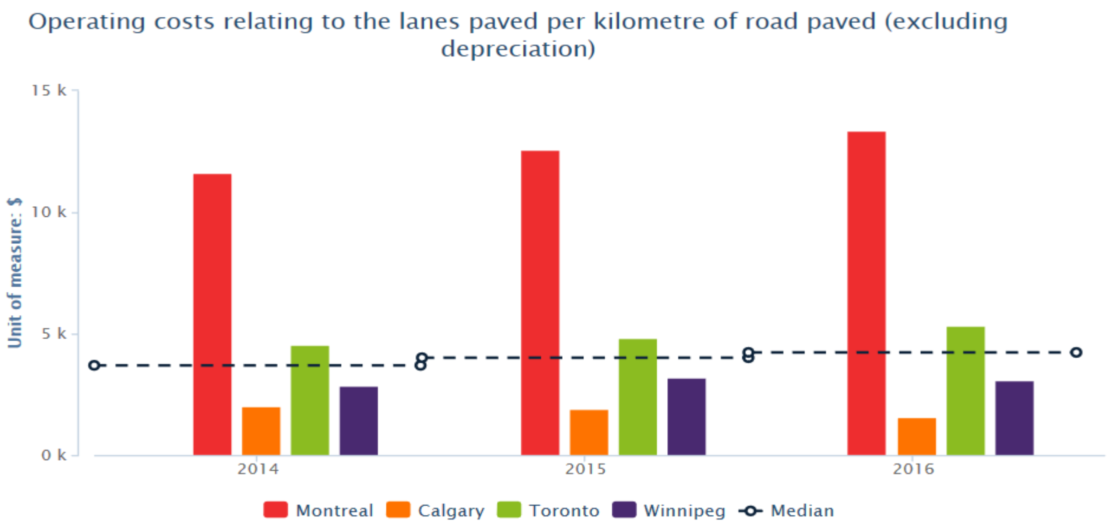


Figure 8.8: *Comparison of the total cost of the roads' maintenance per kilometer among Canadian cities (excluding depreciation) (Ville de Montréal 2017b)*

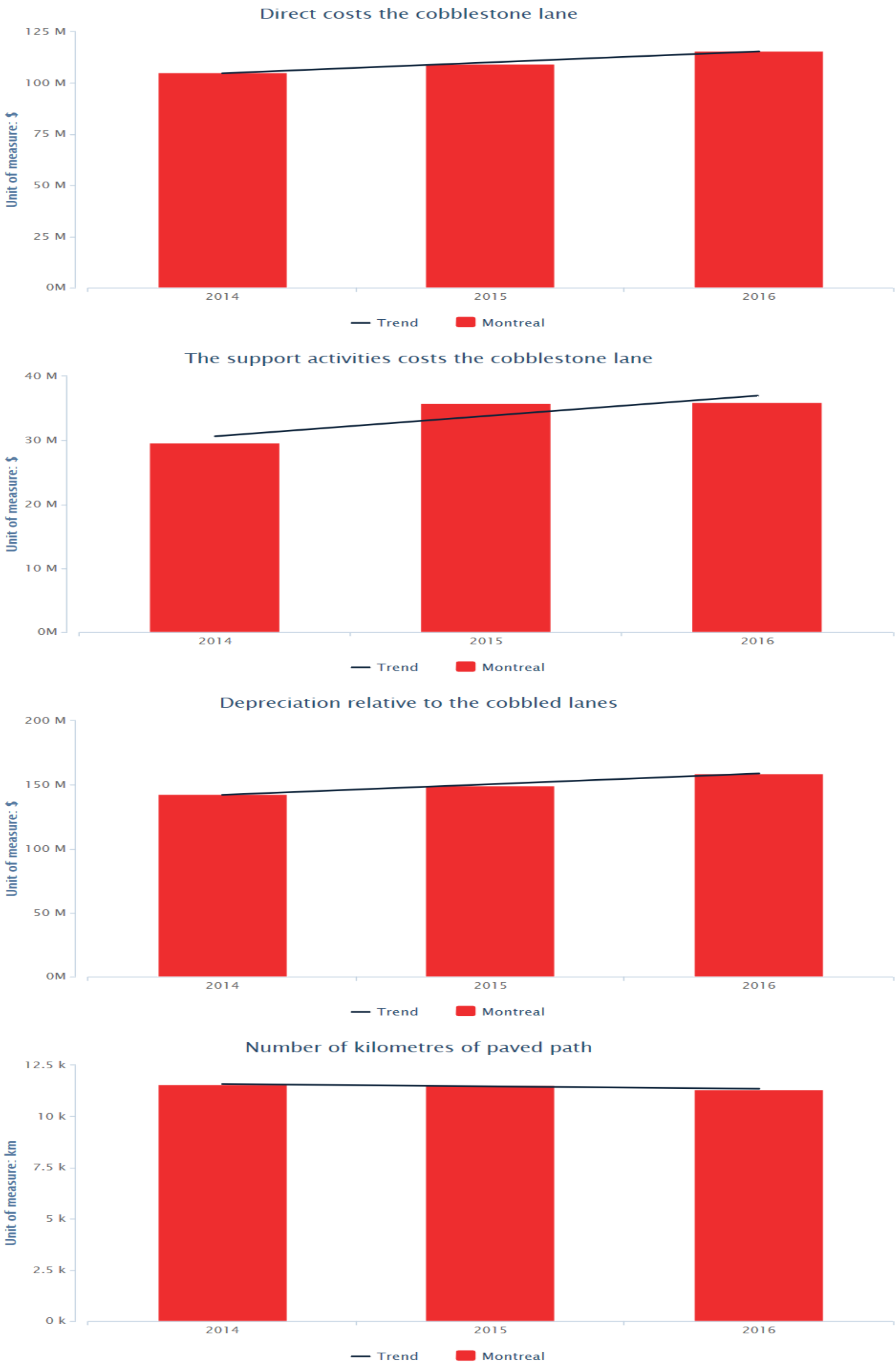


Figure 8.9: *Variables analysis for the total cost of the roads' maintenance per kilometer (Ville de Montréal 2017b)*

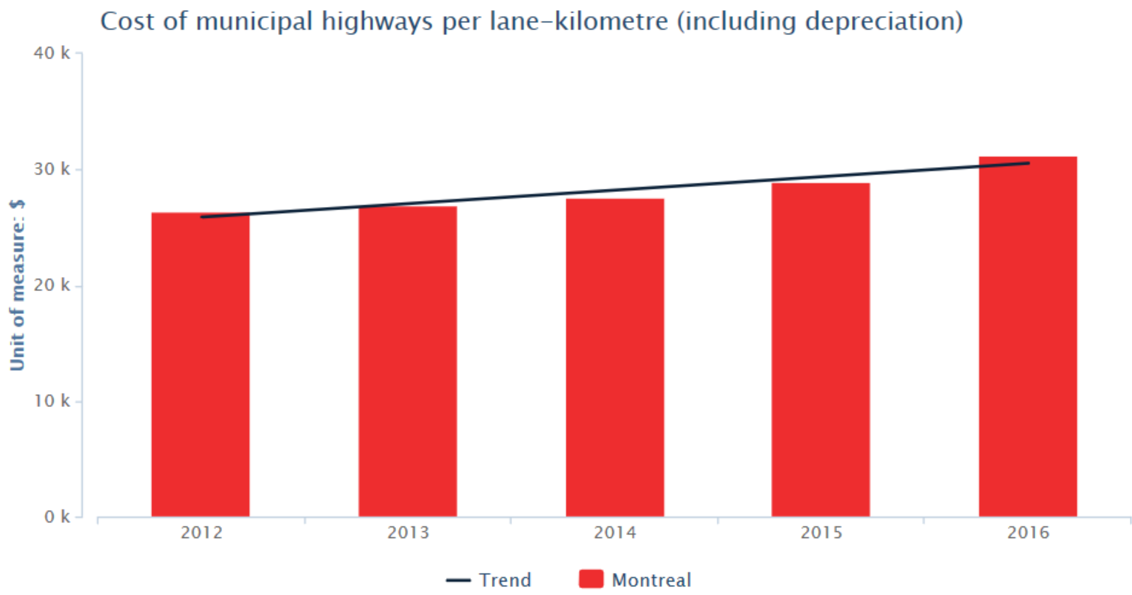


Figure 8.10: *Costs of municipal roads per lane-kilometer (Ville de Montréal 2017b)*

Table 8-7: *Analytical table for the costs of municipal roads per lane-kilometer (Ville de Montréal 2017b)*

	2012	2013	2014	2015	2016
Cost of the municipal road activity	129 542 000	128 154 385	126 619 000	132 320 000	141 294 000
Services - municipal highways	3 385 000	3 321 988	4 358 000	4 525 000	4 252 000
On the road (MAMOT) depreciation	178 555 000	187 161 000	196 400 000	205 194 000	216 603 000
Number of kilometres of road	11 560	11 560	11 560	11 520	11 329
Cost of municipal highways per lane-kilometre (including depreciation)	26 359	26 989	27 566	28 905	31 216
Gap with previous year	-	2.4%	2.1%	4.9%	8.0%
Evolution					18.4%

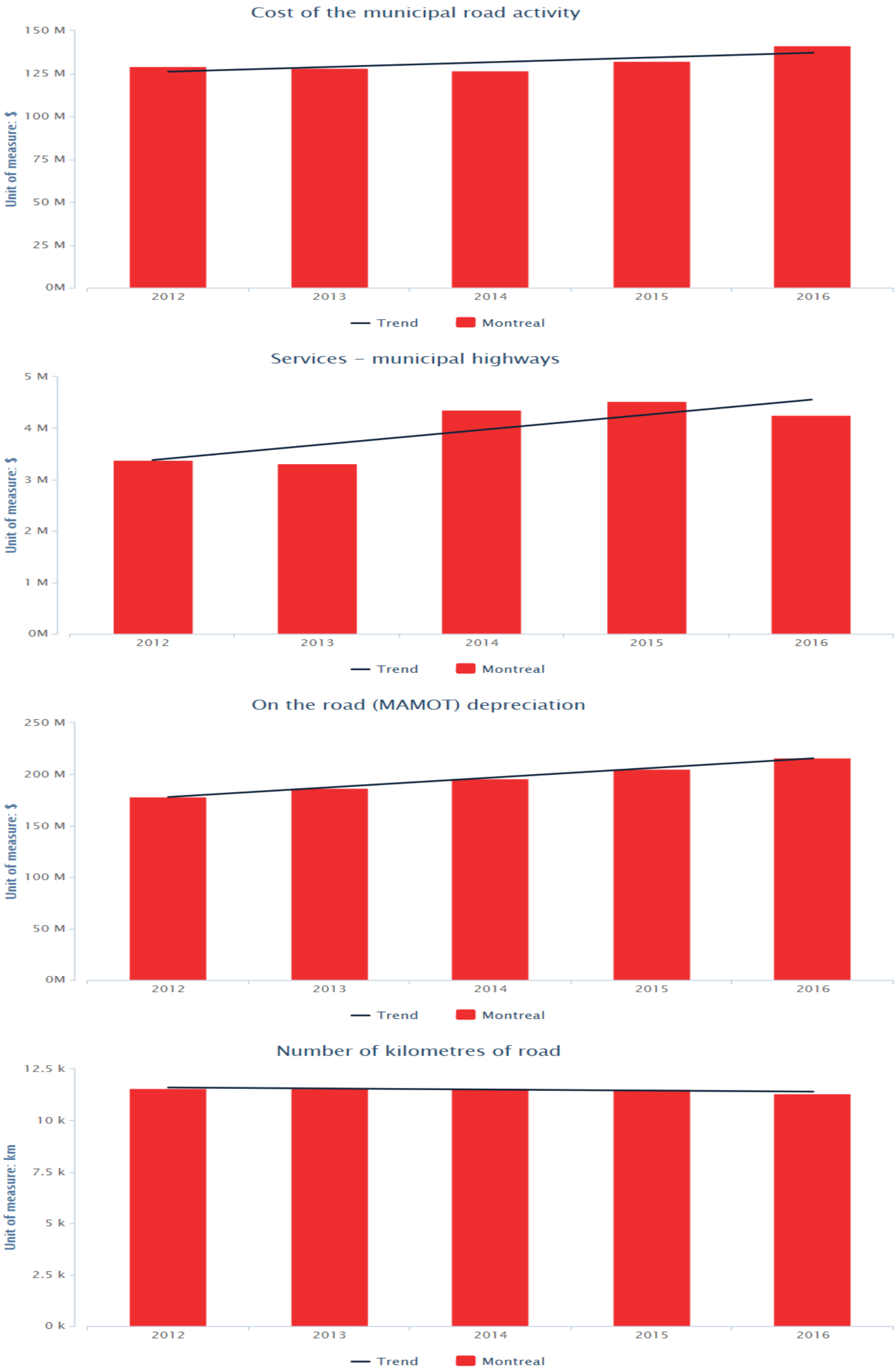


Figure 8.11: *Variables analysis for the costs of municipal roads per lane-kilometer (Ville de Montréal 2017b)*

8.2.2 *Water Network*

8.2.2.1 *Physical State*

This indicator identifies the average age of all drinking water lines, excluding connections, for the distribution and transmission. It is calculated according to a weighted average, which is based on the length of each segment identified in the digital assets of the water network. It indicates the average age of the main and secondary water pipes of Montréal's 19 boroughs; Ahuntsic-Cartierville; Anjou; Côte-des-Neiges–Notre-Dame-de-Grâce; Lachine; LaSalle; Le Plateau-Mont-Royal; Le Sud-Ouest; L'Île-Bizard–Sainte-Geneviève; Mercier–Hochelaga-Maisonneuve; Montréal; Montréal-Nord; Outremont; Pierrefonds-Roxboro; Rivière-des-Prairies–Pointe-aux-Trembles; Rosemont–La Petite-Patrie; Saint-Laurent; Saint-Léonard; Verdun; Ville-Marie; and Villeray–Saint-Michel–Parc-Extension. However, it excludes the service connections and hoses to fire hydrants. Montréal has a large water supply system that provides drinking water for a population of nearly 2 million people. The water pipes diameters vary from 0.10 m to more than 2.74 m, lines and are made up of various materials such as; steel; concrete; and plastic (i.e. PVC, etc.). Within the network, certain pipe segments date back to the beginning of the 20th century and are still in service. In general, water lines have an average life expectancy ranging between 80 and 120 years. The probability of failure for the water network could be displayed in Table **8-8** (Hachey 2017).

As displayed in Figure 8.12 and Table **8-9**, the average age of drinking water lines in 2016 was 60.7 years, representing a 1.2% increase compared with 2015. Montréal's water management department are exerting tremendous efforts to reduce the frequency and severity of the risks associated with the provision of the potable water in the territory. These efforts are translated to rehabilitating the aging water pipes, which could be noticed as the age of the network increased by only 1.3 years between 2014 and 2016, as shown in Table **8-9**. The average network age does not necessarily reflect its' condition state, as the city undertakes some rehabilitation works that do not bring the age of the water pipes to 0 but increases the average life expectancy of the water pipes. Thus, to capture the real impact of the replacement and rehabilitation activities, the remaining life approach would be a better indicator than this one. This indicator represents the overall network improvement in terms of age.

On a global scale, Montréal's average age for the water network, estimated at 60.7 years, was close to that of Toronto's water network, estimated at 59.5 years, but significantly far from the median, which was estimated at 51.85 years, as shown in Figure 8.13. There are several factors that affect the age of the infrastructure such as; pipe age; pipe condition, pipe material; and maintenance frequency.

Table 8-8: *Water network probability of failure*

Probability of Failure	Length (Km)	Percentage (%)	Number of corridors
P < 20%	2,962	86%	29,620
50% > P > 20%	356	10%	3,560
80% > P > 50%	87	3%	870
95% > P > 80%	20	1%	200
P > 95%	32	1%	320
Total	***3,457***	***100%***	***34,570***

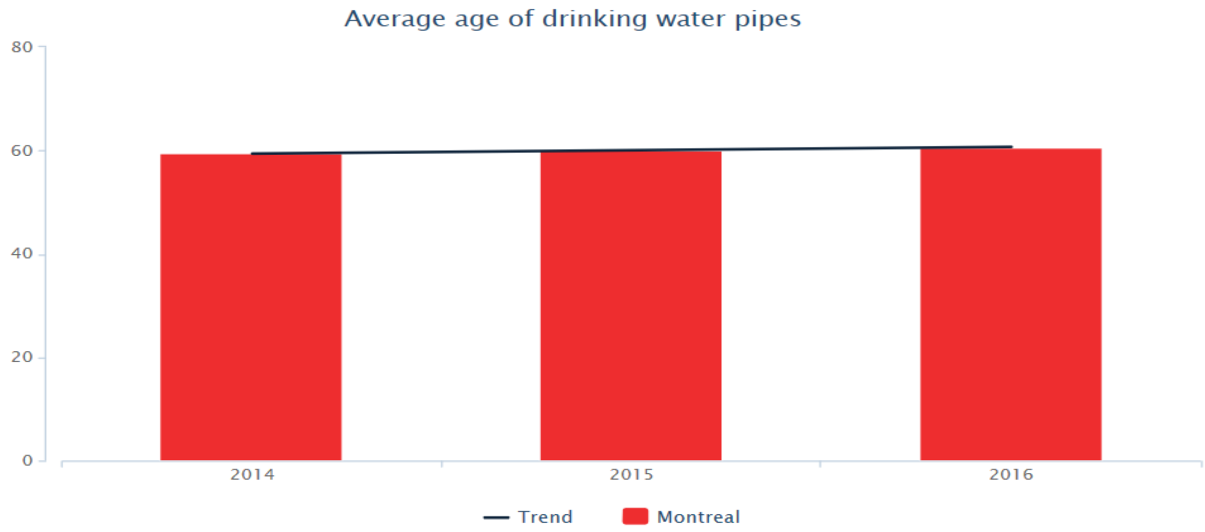


Figure 8.12: *Average age of drinking water pipes*

Table 8-9: *Analytical table for the average age of drinking water pipes*

	2014	2015	2016
Average age of drinking water pipes	59.4	60.0	60.7
Average age of drinking water pipes	59.4	60.0	60.7
Gap with previous year	-	1.0%	1.2%
Evolution			2.2%

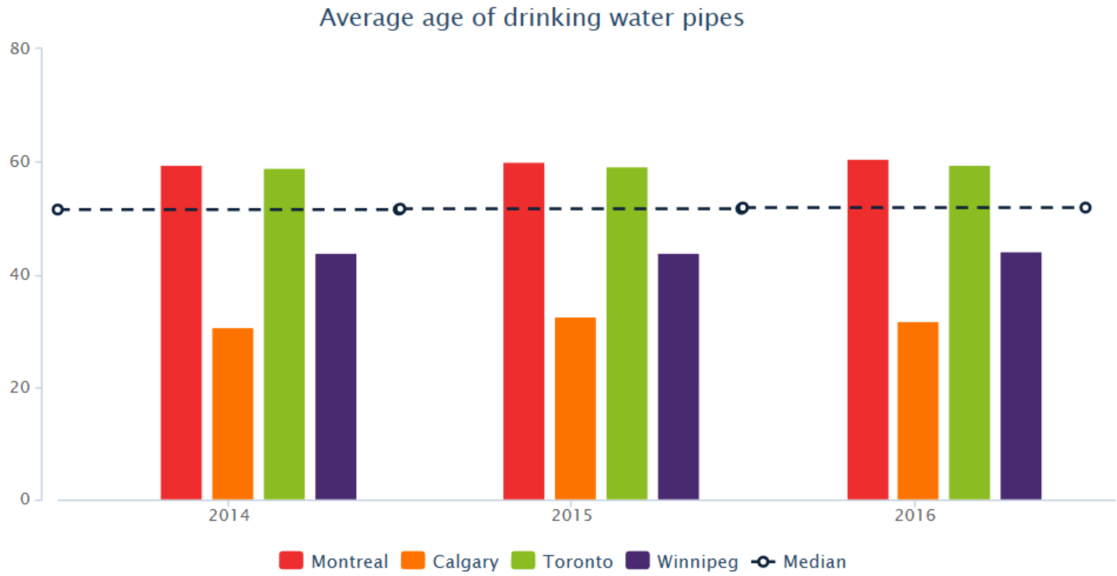


Figure 8.13: *Comparison of the average age of drinking water pipes among Canadian cities*

8.2.2.2 *Pipe Breaks*

This indicator identifies the number of breaks for the main and secondary water pipes per 100 kilometers. As shown in Figure 8.14 and Table 8-10, the breakage rate declined by 22.2% from 2014 to 2016, where the number of water pipe breaks was estimated at 1,018 in 2014 and reached 793 in 2016. It can be recognized that a significant drop of 18.3% occurred between 2015 and 2016, due to the milder temperature, as opposed to the annual average. Even though the pipe break rate is an indicator of the network condition, there are other factors that influence it such as; pipe age, pipe material, pressure, connection density, soil nature, climatic conditions, and winter severity.

On a global scale, the number of water pipe breaks per 100 kilometers, estimated at 18.74, was slightly higher than the median of the cities, estimated at 13.35, as shown in Figure 8.15. The fact that the breakage rate is highly correlated with the network age, which is favorable to some cities, explains the significant difference due to the lower average ages of the existing pipes. There are numerous factors that impact the number of breaks such as; (1) infrastructure age, where the age and condition of the water distribution network, as well as the pipe materials and maintenance frequency, contributes to the number of breaks; (2) urban density, where the proximity of the lines to other facilities increase the repair and replacement costs; and (3) weather condition, where harsh impacts on the water pipes are associated with the frequent and severe climatic conditions. The mathematical formulation of the water pipe breaks could be displayed in Equation 8.4. Details about the variables could be displayed in Figure 8.16.

$$\text{Number of water breaks per 100 kilometer} = \left(\frac{\textit{Number of water main breaks}}{\textit{Length of drinking water distribution/transmission lines (km)}}\right) * 100 \qquad (8.4)$$

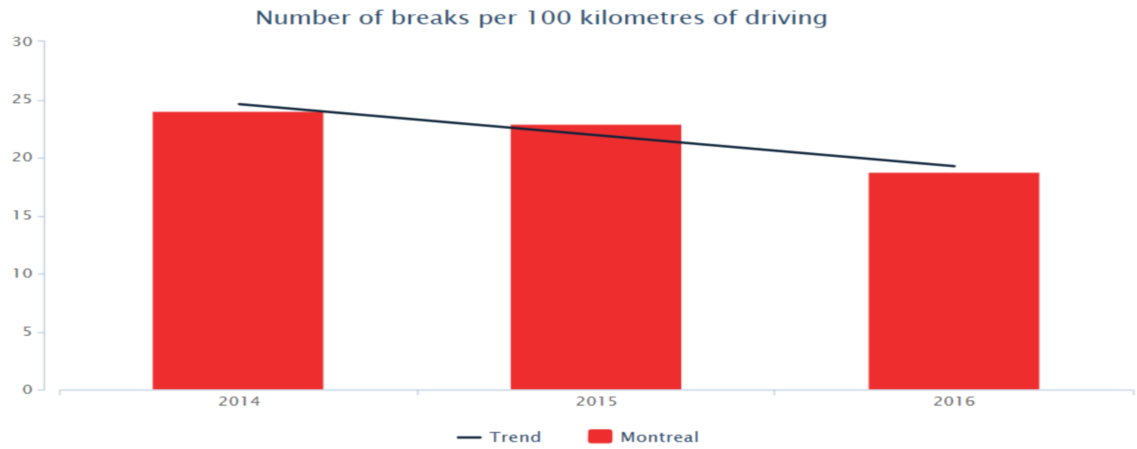


Figure 8.14: *Number of breaks per 100 kilometers of driving*

Table 8-10: *Analytical table for the number of breaks per 100 kilometers of driving*

	2014	2015	2016
Number of water main breaks	1 018	970	793
Length in km of drinking water distribution/transmission lines	4 226	4 226	4 231
Number of breaks per 100 kilometres of driving	24,09	22.95	18.74
Gap with previous year	-	-4,7%	-18,3%
Evolution			-22,2%

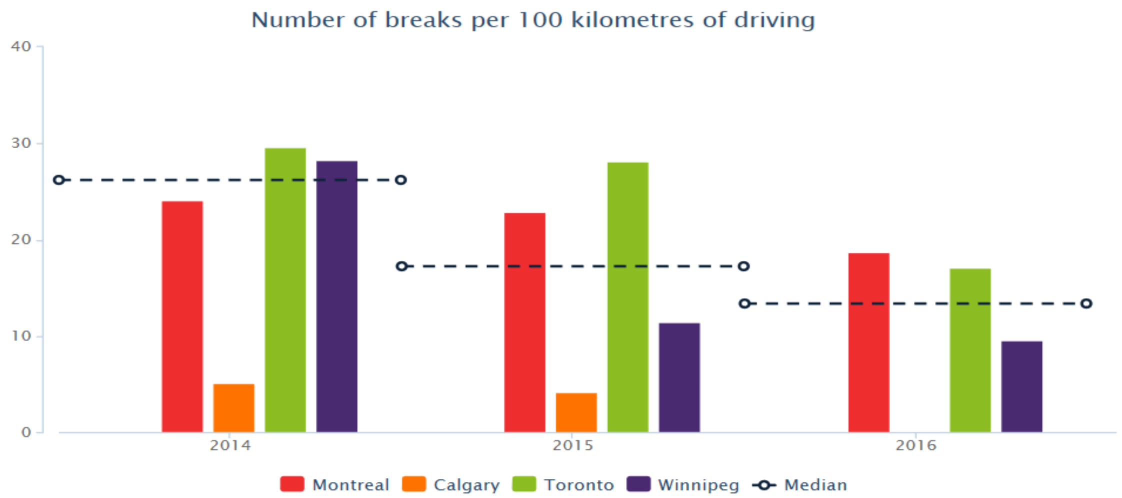
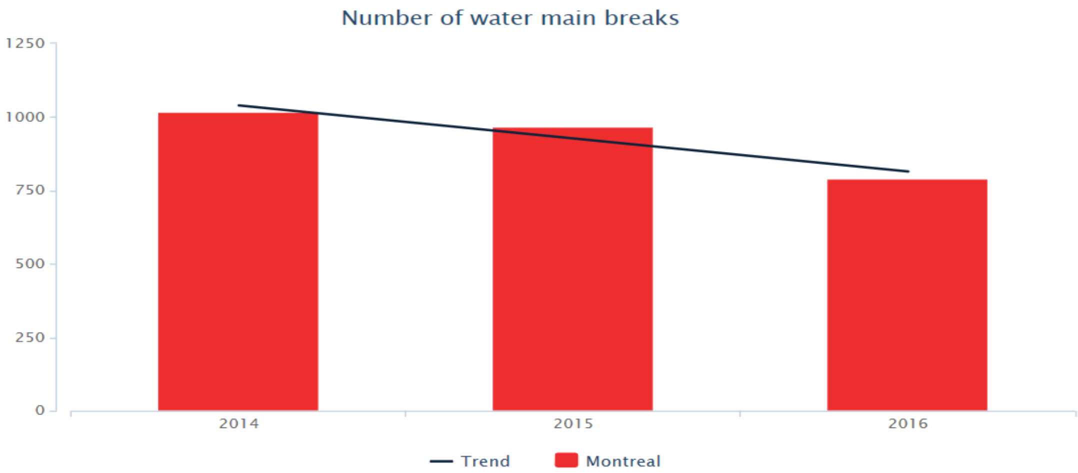


Figure 8.15: *Comparison of the number of breaks per 100 kilometers of driving among Canadian cities*



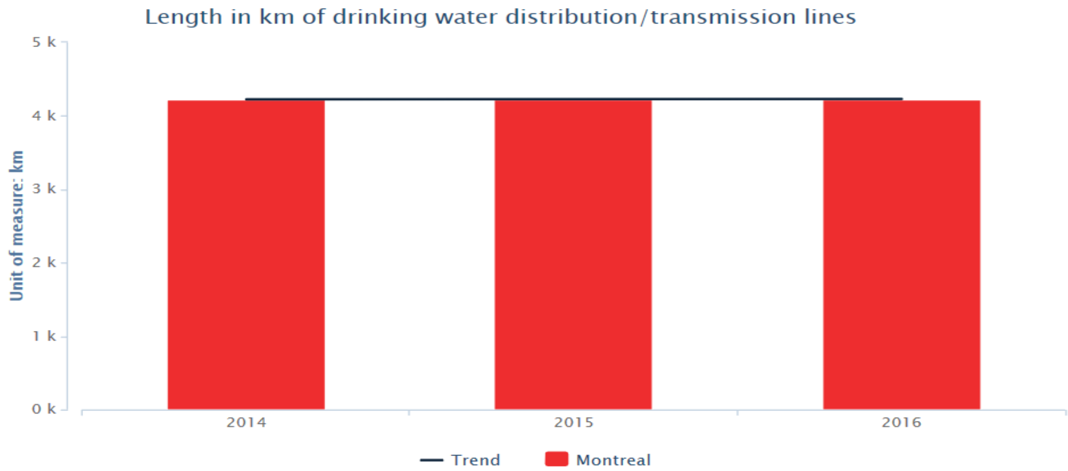


Figure 8.16: *Variables analysis for the number of breaks per 100 kilometers of driving*

8.2.2.3 *Financial*

The financial data was represented via three indicators: (1) cost of drinking water per kilometer of driving or per cubic meter of water; (2) operating cost for distribution/transmission of drinking water per kilometer of water supply pipe network; and (3) total cost of the treatment and distribution/transmission of drinking water per megaliter of treated water. The 1st indicator considers the costs of exploitation and maintenance of the drinking water distribution network as well as the maintenance of tanks and pumping stations. It covers the main and secondary water pipes network. Furthermore, it includes the depreciation expenses subtracted from the rendered services (i.e. income for the installation of water service). Moreover, it includes indirect costs of administrative and technical support. As displayed in Figure 8.17 and Table 8-11, the cost of the activity remained constant between 2015 and 2016 because of the increased depreciation that took place due to the significant amount of investments in the network renewal program. Accordingly, it resulted in an equivalent reduction in the maintenance costs.

However, an increase of 19.4% was noticed between 2012 and 2013, which is a result of the increased maintenance costs, as the city started taking proactive measures to deal with the aging and obsolescence of its water distribution network. In summary, there was an overall increase of 33.6% between 2012 and 2016, which reflects the efforts to enhance the network condition state and overcome the issues of aging and obsolescence. Similarly, Figure 8.18 displays the cost of drinking water per cubic meter of water. It is recognized that the overall cost increased by 2.2% between 2015 and 2016, due to the drop in the quantities of treated drinking water. The quantities of the treated drinking water dropped from 647,438 m^3 in 2015 to 588,337 m^3 in 2016, resulting in this difference between the two indicators, as shown in Figure 8.19. However, the indicator displayed an overall increase of 44.2% between 2012 and 2016 because of the increased number of interventions to address the lack of maintenance, experienced during the last decade, as reflected in the depreciation increase. There are several factors that affect the cost of drinking water per kilometer of driving or per cubic meter of water such as; water saving policy; network condition state; water plant capacity; obsolescence of the maintenance equipment; leak detection program; depreciated capital; population; topography; and methods of government agreements (i.e. in-house, PBC, PPP, etc.). The mathematical formulation of the cost of drinking water per kilometer of driving and per cubic meter of water could be displayed in Equations 8.5 and 8.6 respectively. Details about the variables could be displayed in Figure 8.20.

$$\text{Cost of drinking water per kilometer of driving} = \frac{Cost\ of\ drinking\ water\ distribution - Drinking\ water\ network\ services + Depreciation\ of\ drinking\ water\ network}{Length\ of\ drinking\ water\ distribution/transmission\ lines\ (km)} \tag{8.5}$$

$$\text{Cost of drinking water per cubic meter of water} = \frac{Cost\ of\ drinking\ water\ distribution - Drinking\ water\ network\ services + Depreciation\ of\ drinking\ water\ network}{Volume\ of\ treated\ drinking\ water\ (m^3)} \tag{8.6}$$

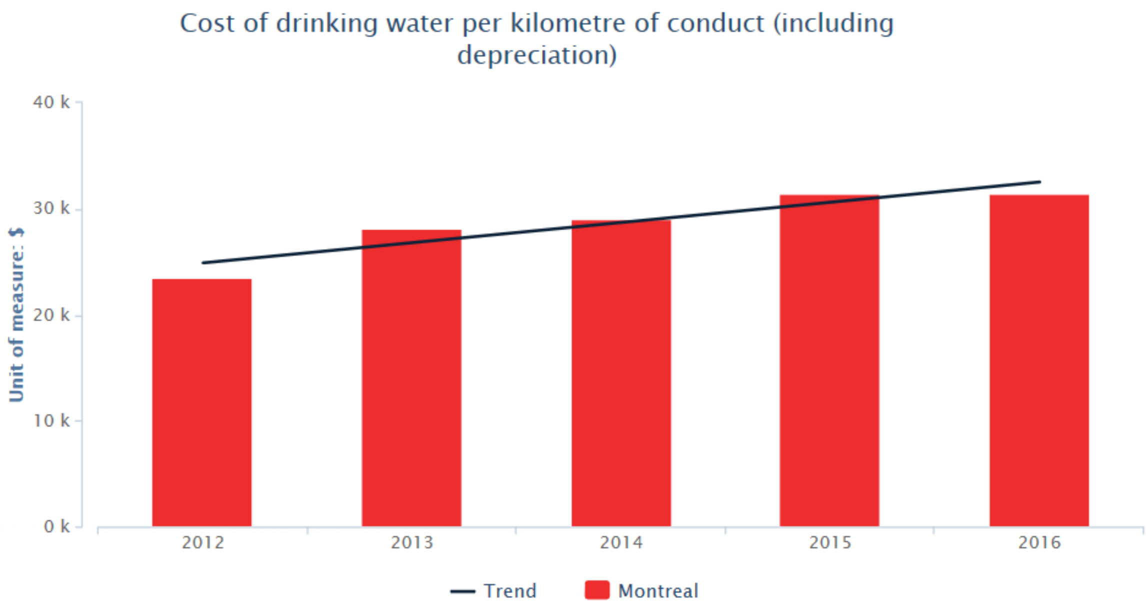


Figure 8.17: *Cost of drinking water per kilometer of driving*

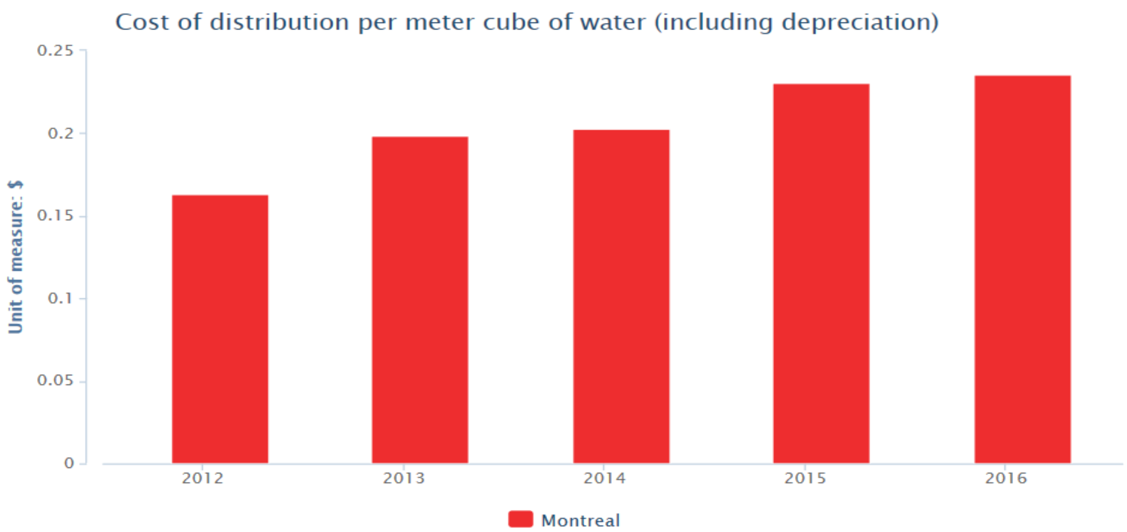


Figure 8.18: *Cost of drinking water per cubic meter of water*

Table 8-11: *Analytical table for the cost of drinking water per kilometer of driving*

	2012	2013	2014	2015	2016
The distribution of drinking water (MAMOT) activity cost	61 587 000	78 883 004	81 593 000	89 063 000	84 101 000
Services related to the distribution of drinking water (MAMOT) network	620 000	622 301	639 000	988 000	1 063 000
Amortization of the distribution network of drinking water (MAMOT)	40 721 000	43 189 000	47 081 000	50 298 000	55 562 000
Length in km (MAMOT) drinking water distribution/transmission lines	4 320	4 320	4 407	4 407	4 408
Cost of drinking water per kilometre of conduct (including depreciation)	23 539	28 113	29 053	31 398	31 443
Gap with previous year	-	19.4%	3.3%	8.1%	0.1%
Evolution					33.6%

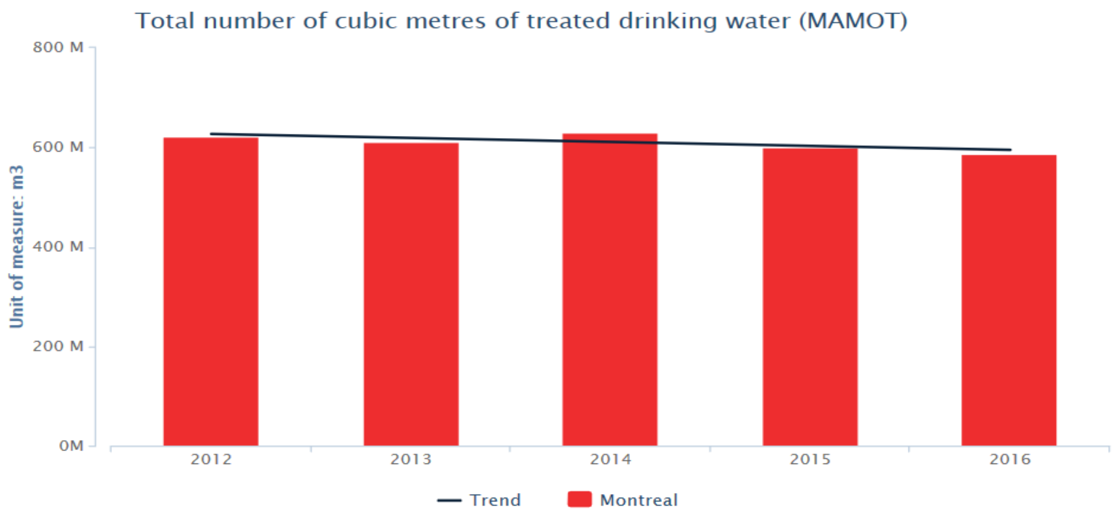


Figure 8.19: *Total volume of treated drinking water*

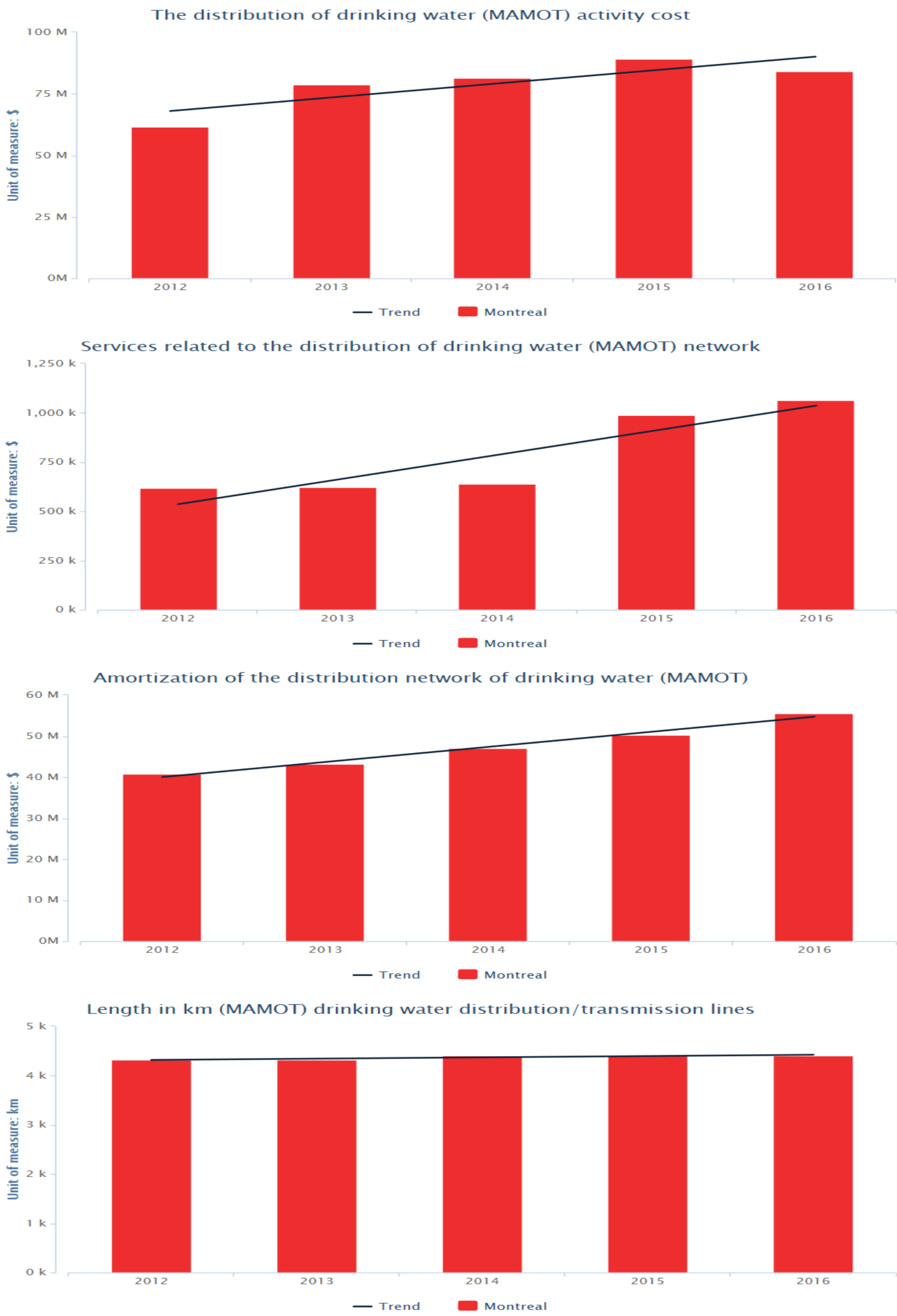


Figure 8.20: *Variables analysis for the cost of drinking water per kilometer of driving*

The 2nd indicator considers the cost of exploitation and maintenance of the drinking water distribution network as well as the maintenance of tanks and pumping stations. It covers the main and secondary water pipe networks and excludes the service connections and hoses to fire hydrants. Furthermore, it includes the depreciation expenses as well as support activities. Moreover, it includes the indirect institutional expenditures such as; budget management, accounting, management of human resources, purchasing, inventory management, information technology, legal services, etc. The capitalization and amortization of capital expenditures are specific to each municipality, where the city of Montréal depreciates its infrastructure over a period of 20 to 40 years, depending on whether it is rehabilitation or reconstruction. However, Toronto depreciates its infrastructure over a period of 60 to 100 years. As displayed in Figure 8.21 and Table 8-12, the cost of the drinking water decreased by 1.9% in 2016 as opposed to 2015, where it dropped from $156M in 2016 to $153.3M in 2015. This drop is due to the reduction in the number of intervention activities (i.e. water pipes repairs). However, there was an overall increase of 11% between 2014 and 2016 because of the increased amortization, estimated at $8.6M, which reflects the significant amount of investments in the network renewal/rehabilitation program. Similarly, Figure 8.22 and Table 8-13 displayed the same trend in Figure 8.21 and Table 8-12, but excluding depreciation.

On a global scale, Montréal displayed 49.5% higher costs in 2016 as opposed to the median of the cities, where Montréal costs were estimated at $36,226 as opposed to a median of $24,245, as shown in Figure 8.23. This sharp increase reflects the low average network age as well as the increasingly ongoing rehabilitation efforts. However, given the fact that most of the works that took place were in high-density areas, the replacement cost per driving kilometer was 70% higher than the average. In 2013, 4% (176 km) of Montréal water network were categorized as "obsolete" and 10% (441 km) was in disrupting condition state. Similarly, Figure 8.24 displayed the same trend as Figure 8.23, but excluding depreciation. There are numerous factors that impact the operating costs of the drinking water such as; (1) amortization, where the amortization costs vary among the municipalities according to the length of the infrastructure's useful life, investment in the capital programs, and capitalization policy; (2) infrastructure age, where the age and the condition of the water distribution network as well as the pipe materials and maintenance frequency contribute to the operating costs of the drinking water; (3) conservation programs, where the extent of water conservation programs can influence the water consumption; (4) urban density, where the proximity of the lines to other facilities increase the repair and replacement costs; (5) government management structure, where the government structure (i.e. one level of governance vs several levels of governance, where the responsibility is shared among the borough municipalities) influence the operating costs of drinking water; (6) supply and demand, where the operating costs of drinking water is impacted by the water source (i.e. ground water, surface water), treatment costs, number of independent distribution networks, the size of geographical area under service, and the variation in the bid for commercial and residential sectors; (7) treatment plant, where the number, size, and technology of the treatment plants impact the operating costs of drinking water as the current capacity of the treatment plants should meet the normal demand and there should be spare capacity available to meet the demand growth during droughts and emergency conditions; and (8) weather condition, where harsh impacts on the water pipes are associated with the frequent and severe climatic conditions. The mathematical formulation of the operating costs of the drinking water could be displayed in Equation 8.7. Details about the variables could be displayed in Figure 8.25.

$$\text{Operating cost for distribution/transmission of drinking water per kilometer} = \frac{\textit{Direct costs} + \textit{Support costs} + \textit{Depreciation of drinking water network} - \textit{Income from other municipalities}}{\textit{Length of drinking water distribution/transmission lines (km)}} \tag{8.7}$$

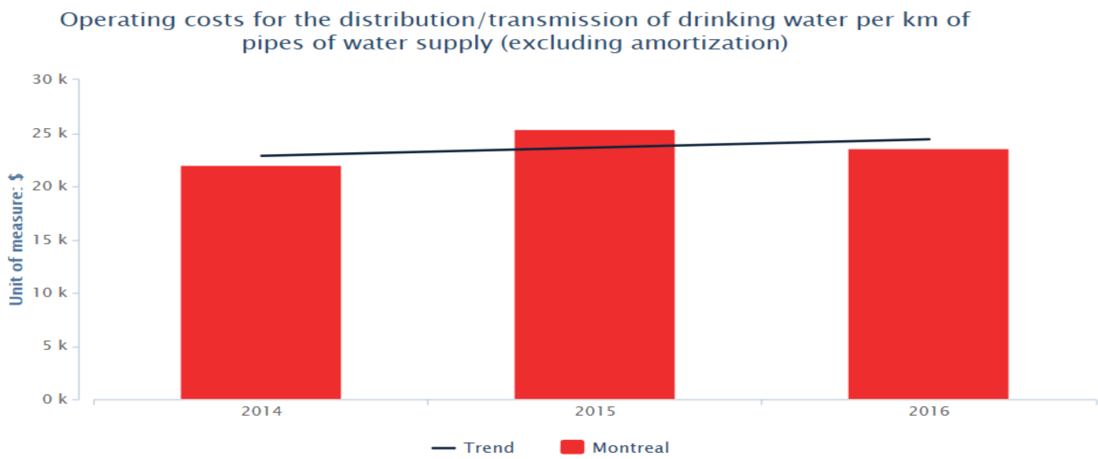


Figure 8.21: *Operating costs for the distribution/transmission of drinking water per kilometer of water supply pipes*

Table 8-12: *Analytical table for the operating costs for the distribution/transmission of drinking water per kilometer of water supply pipes*

	2014	2015	2016
Direct costs to the drinking water distribution network	77 273 476	85 777 028	80 703 125
Support costs of the activities relating to the distribution of drinking water network	15 678 583	21 370 976	18 938 280
Depreciation on the drinking water distribution network	44 982 199	48 858 039	53 631 954
Income from other municipalities related to the drinking water distribution network	0	0	0
Length in km of drinking water distribution/transmission lines	4 226	4 226	4 231
Total cost for the distribution/transmission of drinking water per km of water distribution lines	32 639	36 916	36 226
Gap with previous year	-	13.1%	-1.9%
Evolution			11.0%

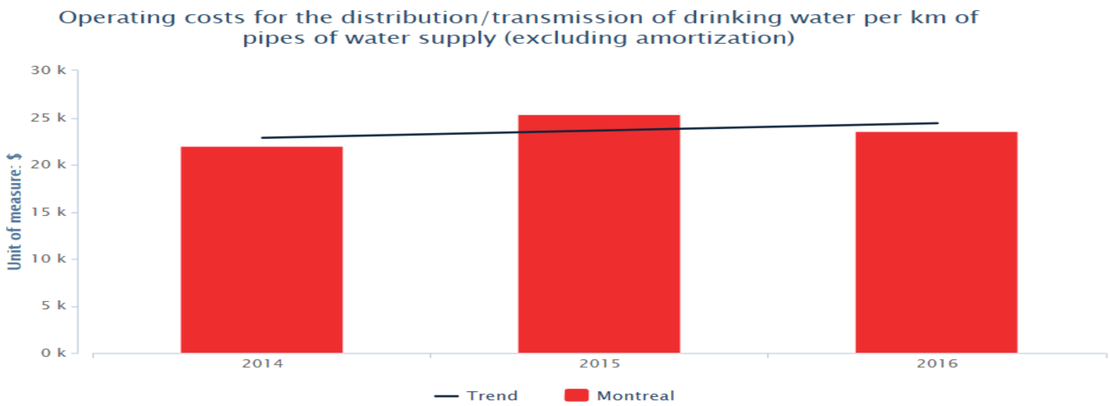


Figure 8.22: *Operating costs for the distribution/transmission of drinking water per kilometer of water supply pipes (excluding depreciation)*

Table 8-13: *Analytical table for the operating costs for the distribution/transmission of drinking water per kilometer of water supply pipes (excluding depreciation)*

	2014	2015	2016
Operating costs for the distribution/transmission of drinking water per km of distribution lines of water (excluding amortization)	21 995	25 354	23 550
Gap with previous year	-	15.3%	-7,1%
Evolution			7.1%

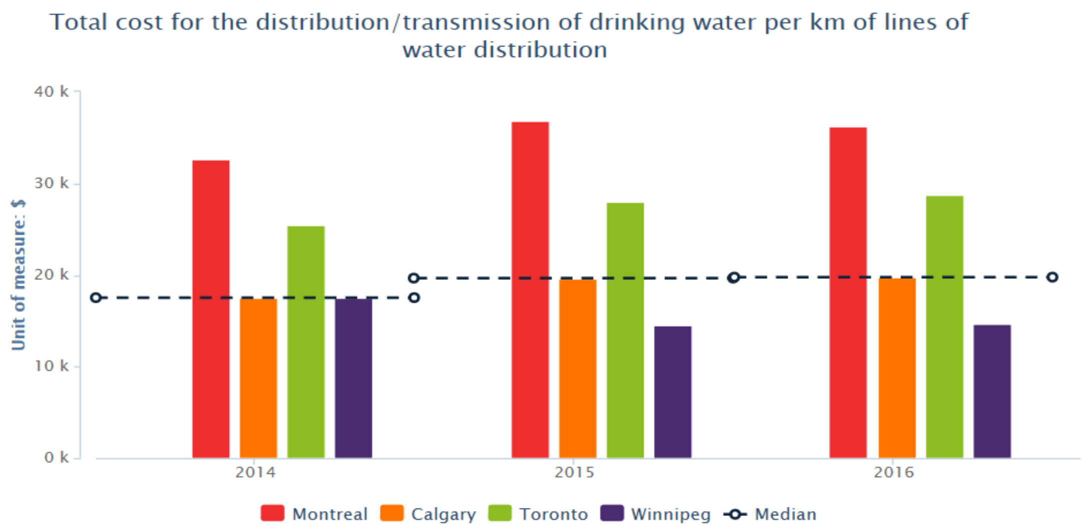


Figure 8.23: *Comparison of the operating costs for the distribution/transmission of drinking water per kilometer of water supply pipes among Canadian cities*

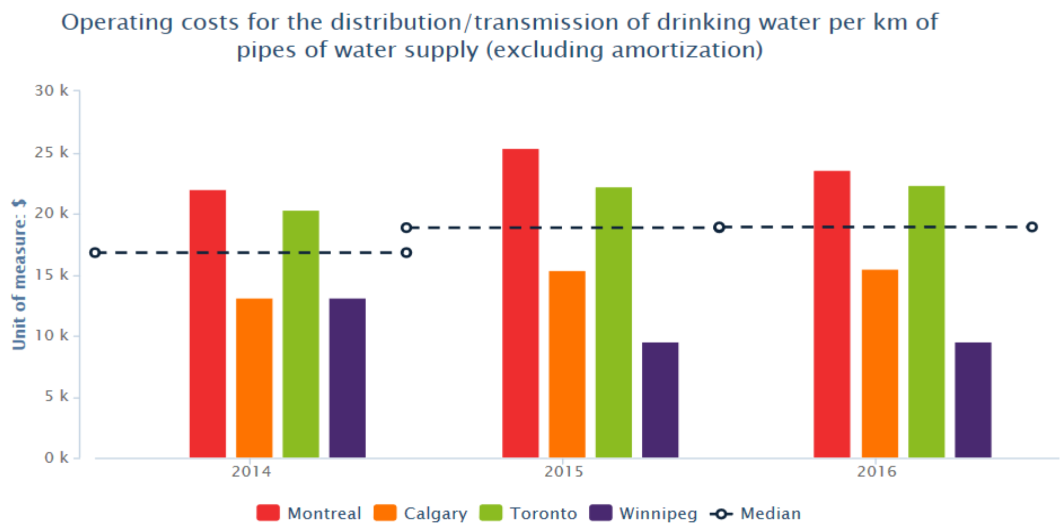


Figure 8.24: *Comparison of the operating costs for the distribution/transmission of drinking water per kilometer of water supply pipes among Canadian cities (excluding depreciation)*

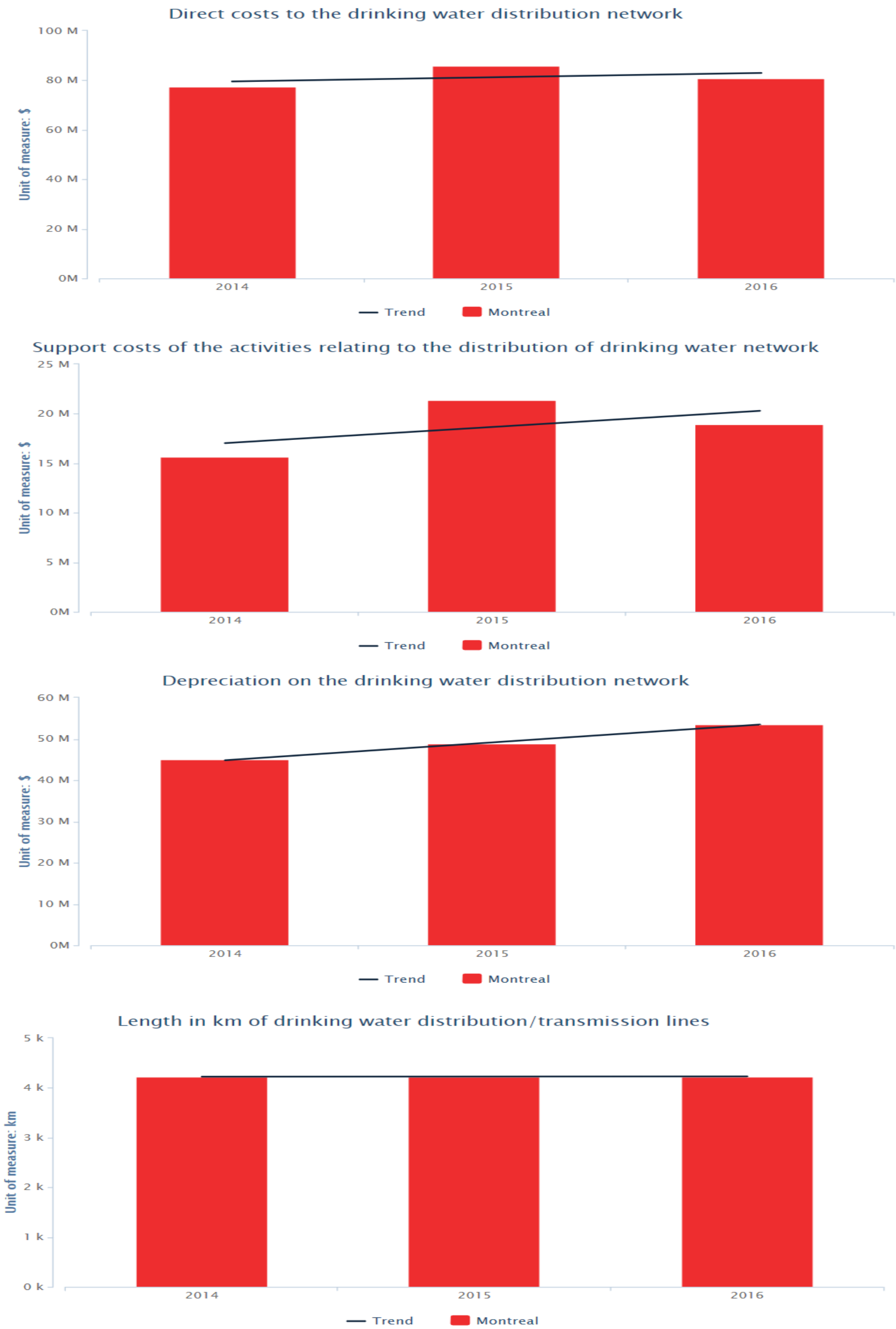


Figure 8.25: *Variables analysis for the operating costs for the distribution/transmission of drinking water per kilometer of water supply pipes*

The 3rd indicator considers the cost of supply and treatment of drinking water, the operation of water treatment plants, water quality analysis, exploitation and maintenance of the drinking water distribution network as well as the maintenance of tanks and pumping stations. It covers the main and secondary water pipe networks and excludes the service connections and hoses to fire hydrants. Furthermore, it includes the depreciation expenses as well as the support activities. Moreover, it includes the indirect institutional expenditures such as; budget management, accounting, management of human resources, purchasing, inventory management, information technology, legal services, etc. The city of Montréal operates six drinking water production plants to serve the population. Due to the pipe leakage and breakage, the city produces an extra volume of drinking water than what it needs. Montréal treatment plants produce 1,650 megaliters of drinking water per day, which is the highest production among the other cities included in the comparison. The capitalization and amortization of capital expenditures are specific to each municipality. The city of Montréal depreciates its water treatment plants and drinking pipe network over a period of 25 and 40 years respectively. As displayed in Figure 8.26 and Table 8-14, the total treatment and distribution costs per megaliter increased by 4.4% in 2016 as opposed to 2015 because of the increased amortization, which is estimated at $12M. The increased amortization reflects the significant investments in the network renewal/rehabilitation program. The city has renewed more than 1% of the drinking water network in 2016 and intends to increase the renewal pace in the upcoming years to counter the impact of aging and reduce the maintenance deficit. Furthermore, the total treatment and distribution costs per megaliter increased by 19.1% between 2014 and 2016 due to the increase in the number of intervention activities related to secondary water pipes repairs associated with the reduction in the drinking water volume, which dropped from 647,438 m3 in 2015 to 588,337 m3 in 2016. This reduction reflects the enhanced renewal program, systematic leak detection and repair, and regulated usage of drinking water through installing meters for industries, business, and institutions. Similarly, Figure 8.27 and Table **8-15** displayed the same trend of Figure 8.26 and Table 8-14, but excluding depreciation.

On a global scale, Montréal displayed $332 less total treatment and distribution costs per megaliter as opposed to the median in 2016, as displayed in Figure 8.28. Similarly, Figure 8.29 displayed the same trend as Figure 8.28, but excluding depreciation. Montréal produces the water at a competitive cost as opposed to other cities because of those factors: (1) the excellence in the quality of the raw water taken upstream from the factories, requiring little chemical treatment; and (2) economy of scale given the fact that the city of Montréal serves a population of nearly 2 million citizens. The higher production of drinking water per capita is a result of the large population; high loss rate, estimated at 21% annually; and the large number of industries, businesses, and institutions that consume more than 55% of the distributed water. The factors that impact the total cost of the treatment and distribution/transmission of drinking water per megaliter of treated water are similar to the previous indicator. The mathematical formulation of the total cost of the treatment and distribution/transmission of drinking water per megaliter of treated water could be displayed in Equation 8.8. Details about the variables could be displayed in Figure 8.30 and Figure 8.31.

$$\text{Total cost of the treatment and distribution/transmission of drinking water per megaliter of treated water} = \frac{\textit{Direct costs} + \textit{Support costs} + \textit{Depreciation of drinking water network} - \textit{Income from other municipalities}}{\textit{Volume of drinking water (mega liters)}} \tag{8.8}$$

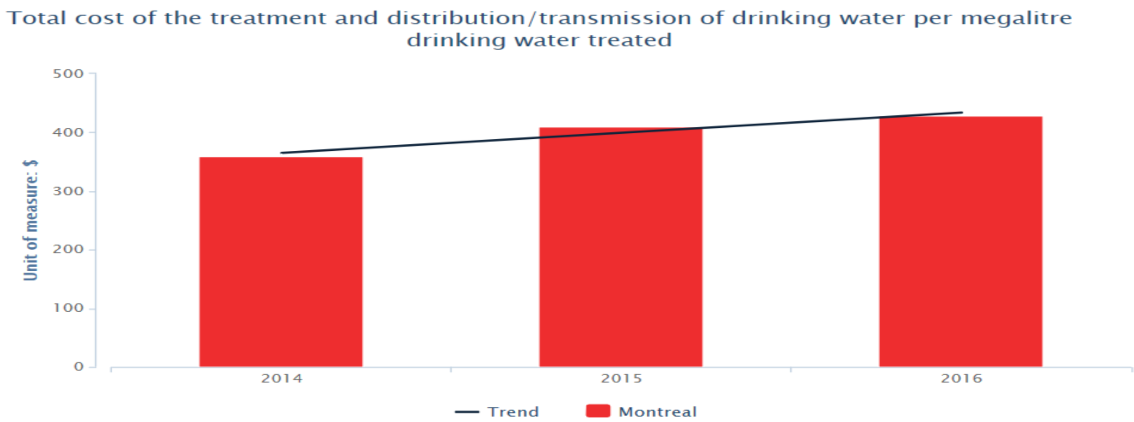


Figure 8.26: *Total cost of the treatment and distribution/transmission of drinking water per megaliter of treated water*

Table 8-14: *Analytical table for the total cost of the treatment and distribution/transmission of drinking water per megaliter of treated water*

	2014	2015	2016
Direct costs to the drinking water distribution network	77 273 476	85 777 028	80 703 125
Support costs of the activities relating to the distribution of drinking water network	15 678 583	21 370 976	18 938 280
Depreciation on the drinking water distribution network	44 982 199	48 858 039	53 631 954
Income from other municipalities related to the drinking water distribution network	0	0	0
Direct costs related to the treatment of drinking water	44 771 104	43 201 046	43 271 525
Support costs of the activities related to the treatment of drinking water	5 187 217	6 542 743	6 084 600
Depreciation on the treatment of drinking water	16 776 672	15 849 185	22 978 706
Income from other municipalities related to the treatment of drinking water	148 207	161 647	155 717
Megalitres of treated drinking water	568 838	539 821	526 359
Total cost of the treatment and distribution/transmission of drinking water per megalitre of water treated	359,54	410,21	428,32
Gap with previous year	-	14.1%	4.4%
Evolution			19.1%

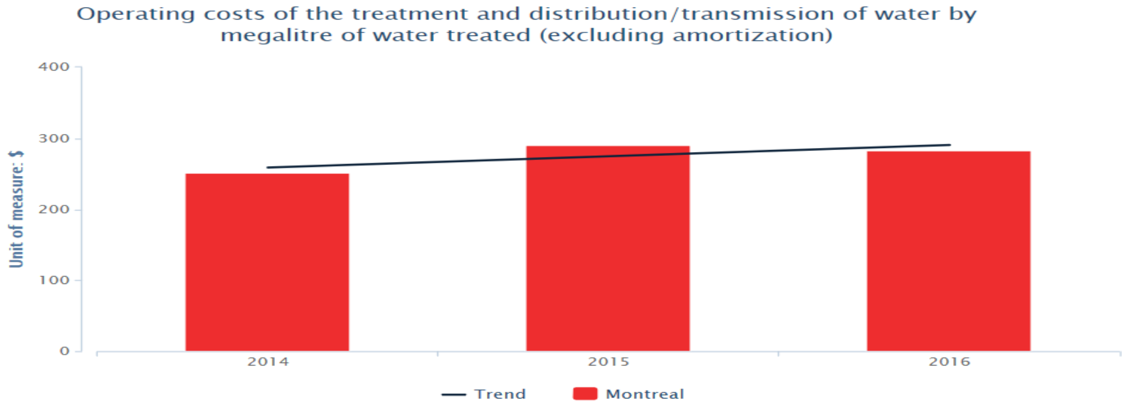


Figure 8.27: *Total cost of the treatment and distribution/transmission of drinking water per megaliter of treated water (excluding depreciation)*

Table 8-15: *Analytical table for the total cost of the treatment and distribution/transmission of drinking water per megaliter of treated water (excluding depreciation)*

	2014	2015	2016
Operating costs of the treatment and distribution/transmission of drinking water per megalitre of water treated (excluding amortization)	250,97	290,34	282,78
Gap with previous year	-	15.7%	-2,6%
Evolution			12.7%

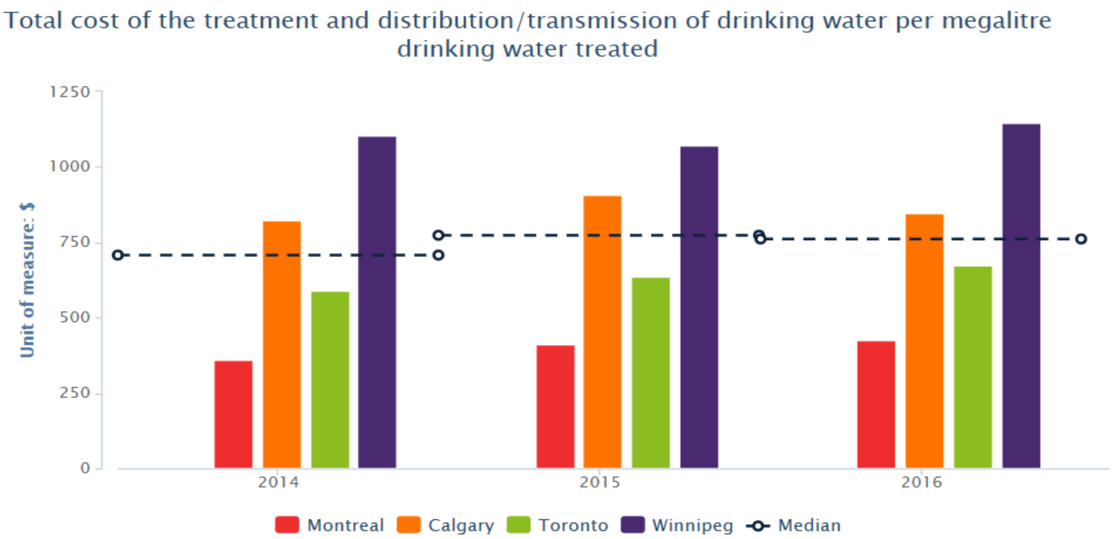


Figure 8.28: *Comparison of the total cost of the treatment and distribution/transmission of drinking water per megaliter of treated water among Canadian cities*

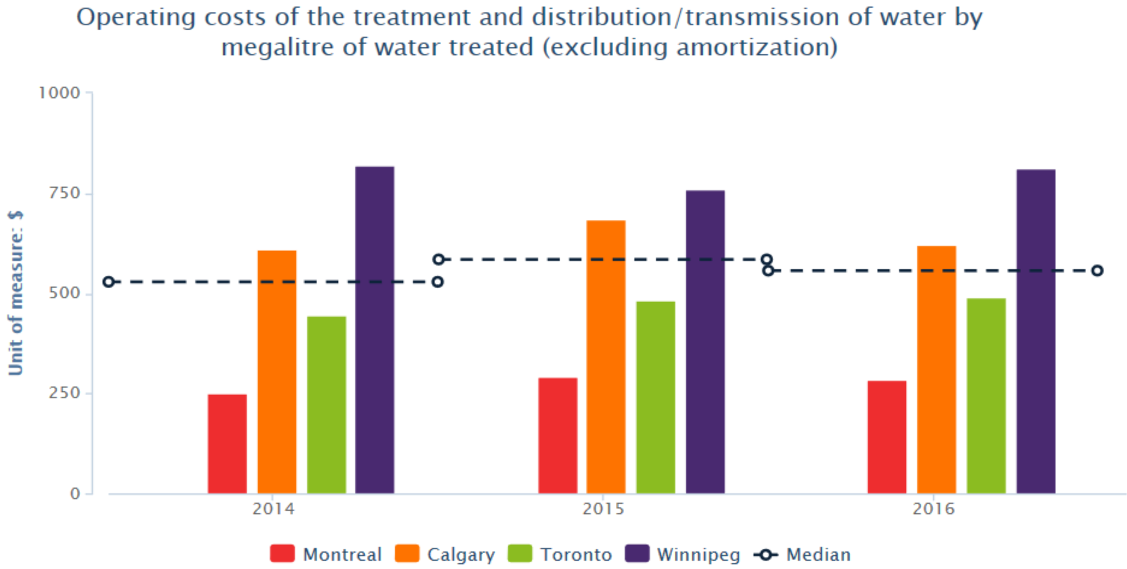


Figure 8.29: *Comparison of the total cost of the treatment and distribution/transmission of drinking water per megaliter of treated water among Canadian cities (excluding depreciation)*

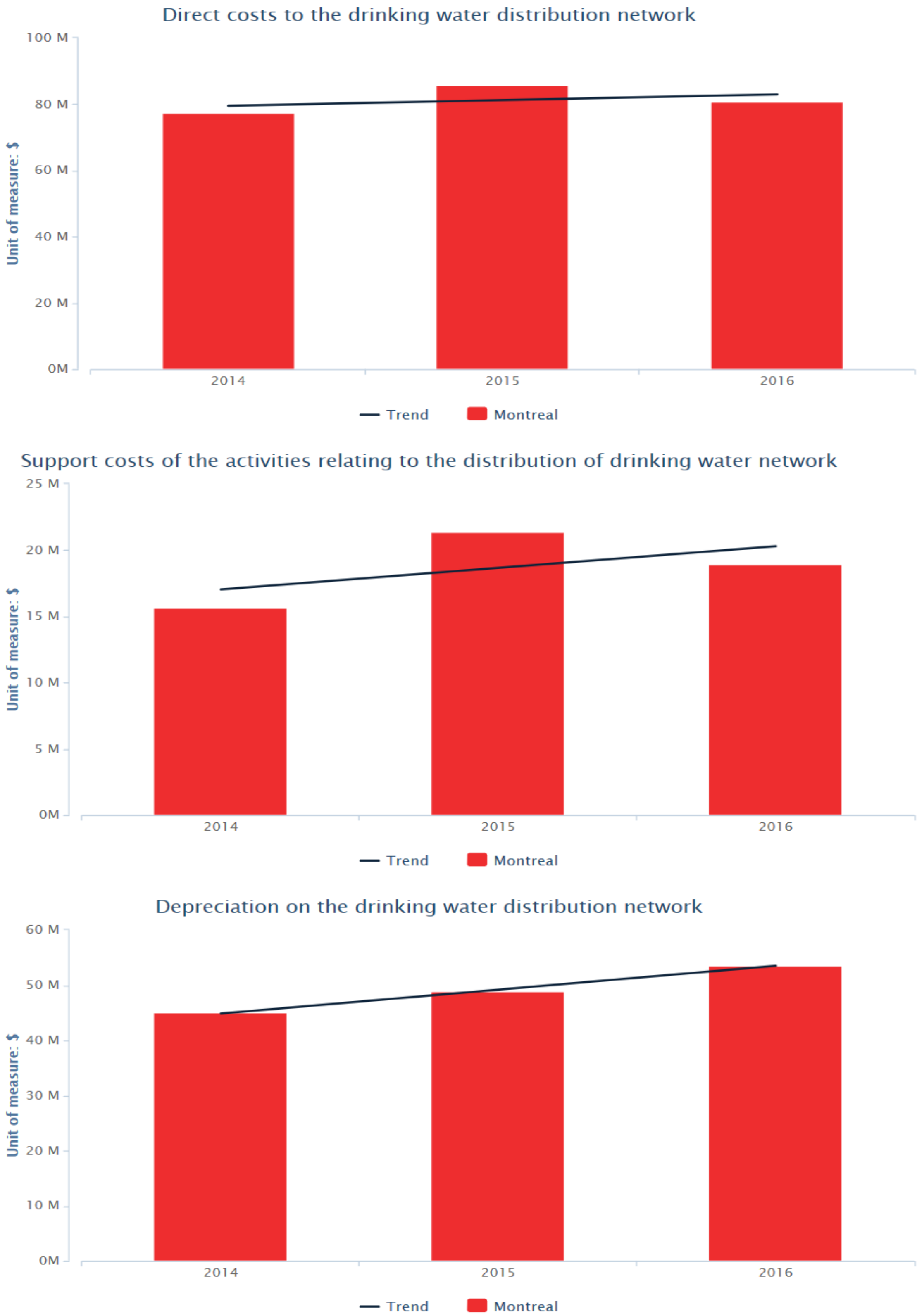


Figure 8.30: *Variables analysis for the total cost of the treatment and distribution/transmission of drinking water per megaliter of treated water (1 out of 2)*

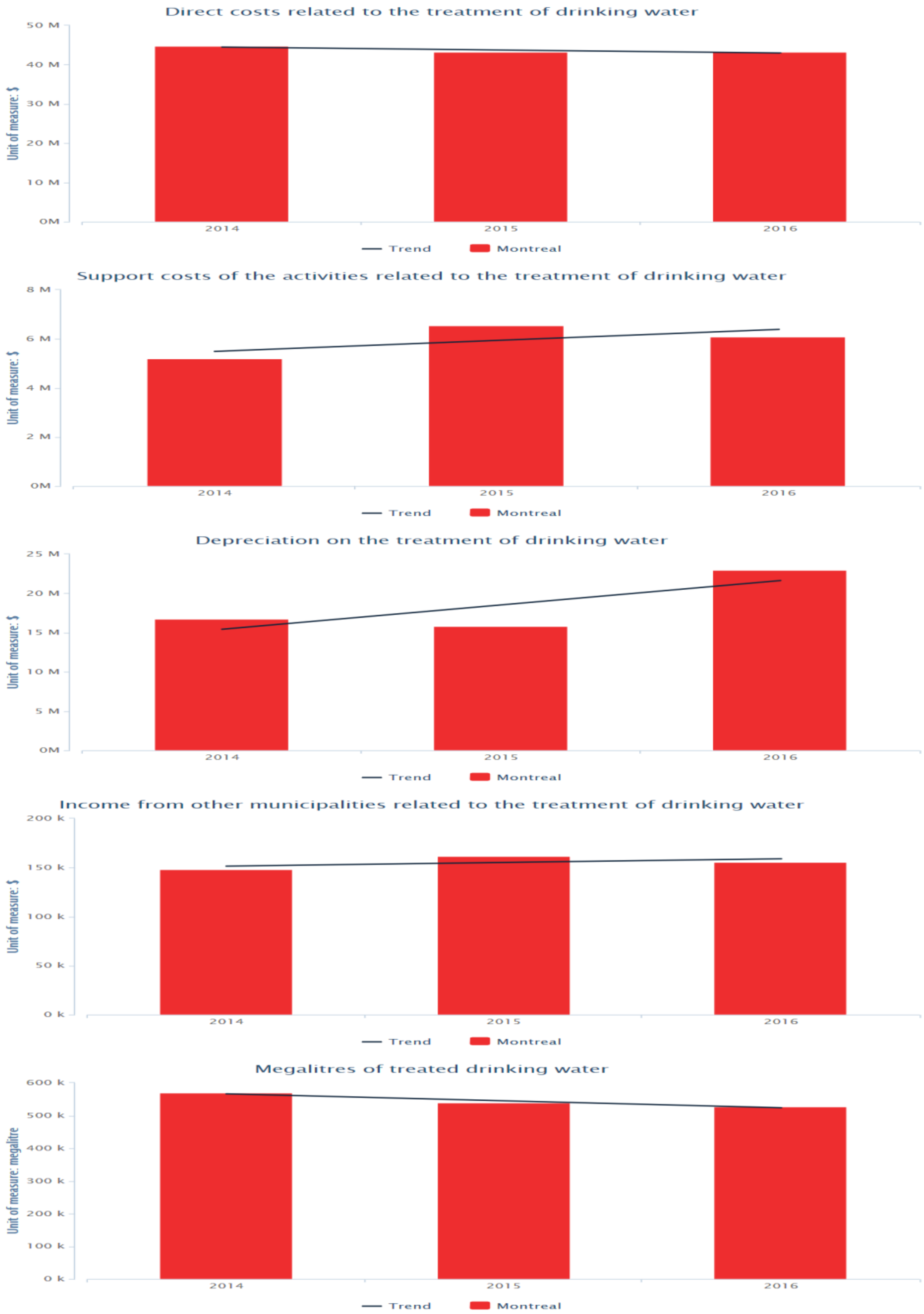


Figure 8.31: *Variables analysis for the total cost of the treatment and distribution/transmission of drinking water per megaliter of treated water (2 out of 2)*

8.2.3 *Combined Sewer and wastewater network*

8.2.3.1 *Physical State*

This indicator identifies the average age of all sewer network, excluding service connections, for the collection and interception of sewage. It is calculated according to a weighted average, which is based on the length of each segment identified in the digital assets of the sewer network. Montréal serves its citizens through a combined sewer and rainwater network of pipes, instead of two separate networks, that collects both sewer and rainwater with an annual capacity of 750,000 megaliters of sewage transported to the wastewater treatment plants. As displayed in Figure 8.32 and Table **8-16**, the average age of sewer lines in 2016 was 60.5 years, representing a 2.7% increase as opposed to 2014. Significant efforts are exerted to rehabilitate the aging pipes and extend their life expectancy. One of the commonly used rehabilitation techniques is the cladding, which aims at promptly undertaking the intervention to reduce the disruption impact on the citizens and corridor users and significantly reduce the intervention costs.

On a global scale, unlike the water network, Montréal's average age for the combined sewer network, estimated at 60.5 years, was a bit better than Toronto's sewer network, estimated at 62.6 years, as well as the median, estimated at 60.6 years, as shown in Figure 8.33. In general, the network age is influenced by the network development pace through time as well as the cities' ability to continue developing and maintaining their existing networks. It would be relatively easier for growing and small cities to maintain a low network average age as opposed to big and developed cities, where the city must mainly rely on replacing the existing networks to influence the network average age. The fact that the city of Montréal has an old and antiquated sewer network stems back to the lack of historical maintenance, which exponentially increases the number of required interventions and causes more breakage and backflow, as will be highlighted later in the following sub-sections. There are several factors that affect the age of the infrastructure such as; pipe age; pipe condition, pipe material; and maintenance frequency.

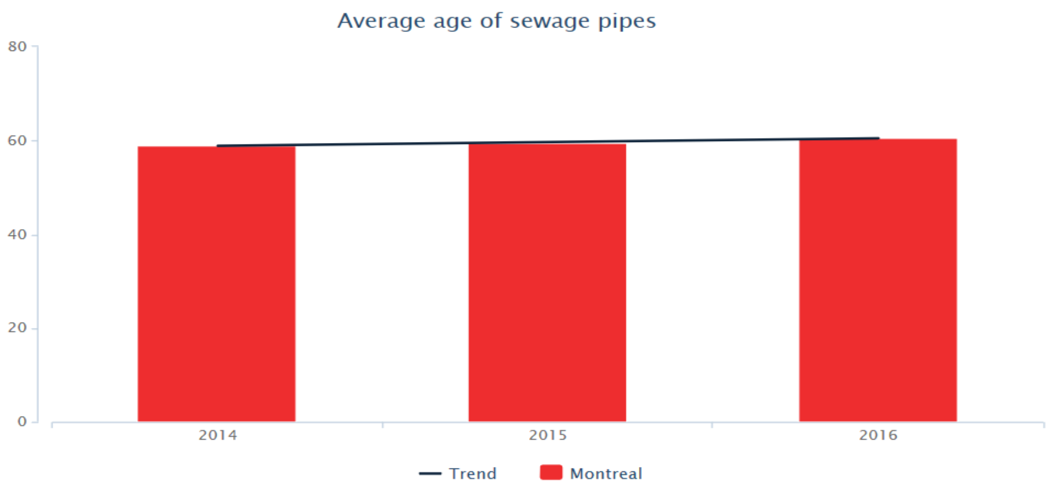


Figure 8.32: *Average age of sewer pipes*

Table 8-16: *Analytical table for the average age of sewer pipes*

	2014	2015	2016
Average age of sewage pipes	58.9	59.6	60.5
Average age of sewage pipes	58.9	59.6	60.5
Gap with previous year	-	1.2%	1.5%
Evolution			2.7%

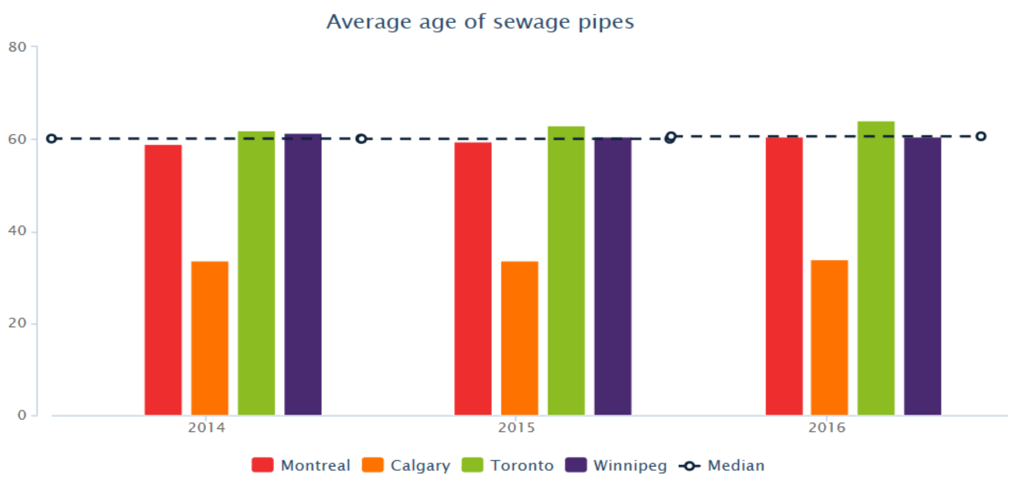


Figure 8.33: *Comparison of the average age of sewer pipes among Canadian cities*

8.2.3.2 *Sewer Back-up*

This indicator identifies the number of sewer back-ups for the main and secondary sewer pipes per 100 kilometers of sewer pipes. The number of sewer back-ups is compiled from the claims for damages during heavy rain or network overloading. It is highly affected by the heavy rains as well as the blockage and pipe breaks. As shown in Figure 8.34 and Table

8-17, the number of sewer back-ups per 100 kilometers of sewer pipes increased by 49.4% between 2015 and 2016, where the number of sewer back-ups was estimated at 4.92 in 2015 and jumped to 7.35 in 2016. Given the fact that the city of Montréal sewer is unitary at 80%, numerous complaints related to sewage backflow is highly correlated to the number of heavy rain events, which have been noticeably increasing in both their frequency and intensity over the past few years. Few sewer back-ups occur due to damage or blockage of the network. However, their weight is negligible compared to those taking place because of the heavy rain. Thus, caution is required while using this indicator as it is highly dependent on the weather condition. The historical rain records resulted in 4,209 sewer backflows, which is at least 5 times greater than the average value.

On a global scale, the number of sewer back-ups per 100 kilometers, estimated at 7.35, exceeded the median of the cities by about 3.25 times, estimated at 4.10, as shown in Figure 8.35. The fact that the city of Montréal has the highest proportion of unitary network among the other cities, the results are highly dependent on climatic conditions (i.e. heavy rain events, storm events). Thus, the city has implemented a valve inspection program to reduce this phenomenon in the combined sewer and wastewater networks. There are numerous factors that impact the number of sewer back-ups such as; (1) infrastructure age, where the age and condition of the sewer distribution network, as well as the maintenance frequency, contribute to the number of sewer back-ups; (2) policies and maintenance practices, where the condition and types of maintenance equipment, as well as the network age, impact the number of sewer back-ups; (3) urban density, where the proximity of the lines to other facilities increase the repair and replacement costs; and (4) weather condition, where harsh impacts on the sewer pipes are associated with the frequent and severe climate conditions. The mathematical formulation of the sewer back-ups could be displayed in Equation 8.9. Details about the variables could be displayed in Figure 8.36.

$$\text{Number of sewer back} - \text{ups per 100 kilometer} = \left(\frac{Number\ of\ sewer\ back{-}ups\ in\ sewer\ pipes}{Length\ of\ sewer\ pipes\ to\ trasport/collection\ of\ wastewater\ sysetm\ (km)}\right) * 100 \quad (8.9)$$

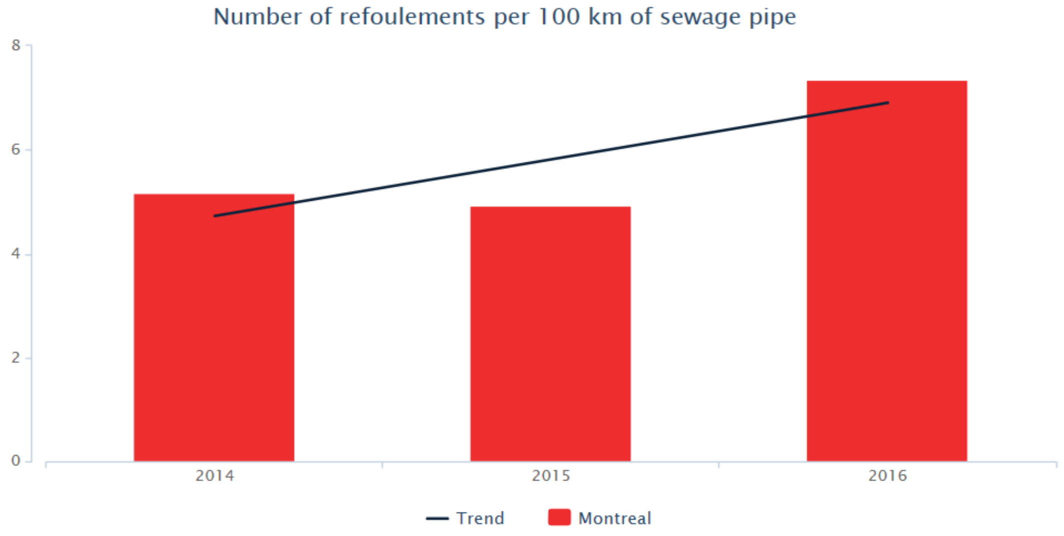


Figure 8.34: *Number of sewer back-ups per 100 kilometers of sewer*

Table 8-17: *Analytical table for the number of sewer back-ups per 100 kilometers sewer*

	2014	2015	2016
Number of refoulements in sewage pipes	213	203	303
Length in km of pipes to transport/collection of wastewater system	4 121	4 123	4 124
Number of refoulements per 100 km of sewage pipe	5,17	4.92	7.35
Gap with previous year	-	-4,8%	49.4%
Evolution			42.2%

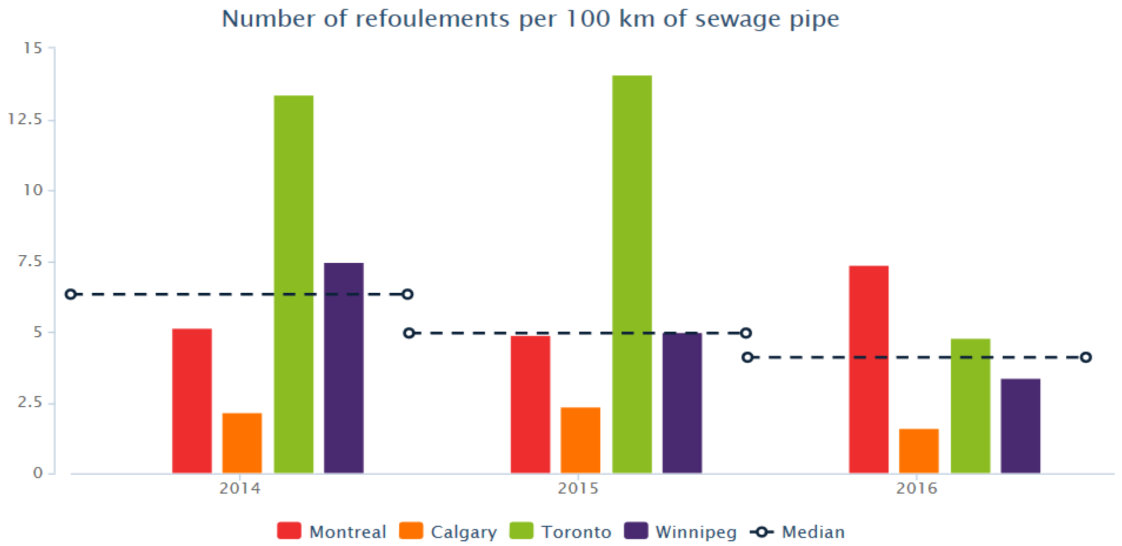


Figure 8.35: *Comparison of the number of sewer back-ups per 100 kilometers sewer among Canadian cities*

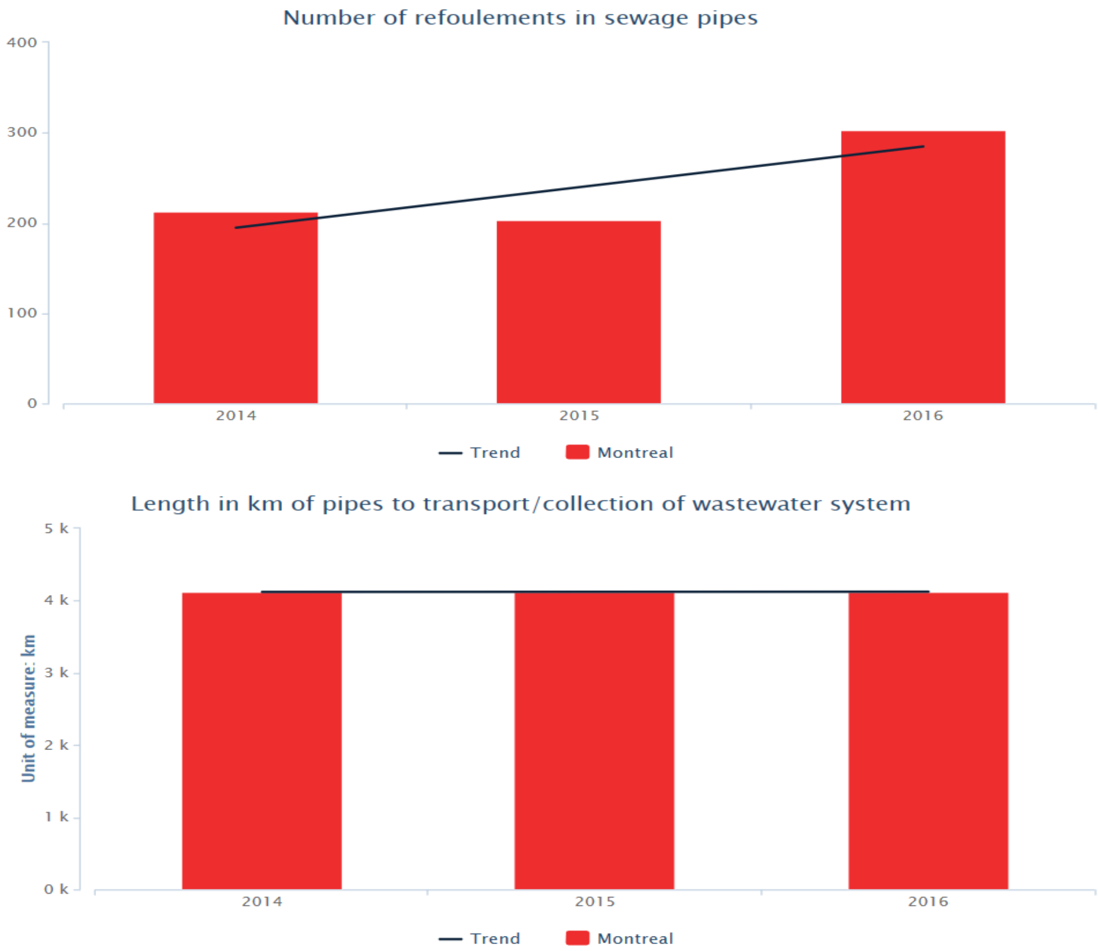


Figure 8.36: *Variables analysis for the number of sewer back-ups per 100 kilometers sewer*

8.2.3.3 *Untreated Sewage*

This indicator computes the estimated percentage of sewage that escaped the treatment system in the main and secondary sewer pipe networks of the city of Montréal. The total volume of untreated wastewater includes the wastewater that escaped from the wastewater treatment facilities, pumping stations and sewage collection system. It was estimated according to the spill duration. This volume is estimated through multiplying the spill duration and the flow measured at each work overflow. Sometimes, due to the high rates of captured stormwater during heavy rains, sewage does not have sufficient capacity to transport all the stormwater and wastewater to the wastewater treatment plant, resulting in overflow of combined stormwater and wastewater to the receiving stream for a short period of time. As shown in Figure 8.37 and Table **8-18**, the estimated percentage of sewage decreased by 37.3% in 2016 as opposed to 2015, which is due to the absence of heavy rains during this period. However, there was an overall increase of 16.9% between 2014 and 2016 due to the reduction in the volume of treated water, where it dropped from 785,358 megaliters in 2014 to 723,289 megaliters.

On a global scale, the estimated percentage of wastewater that escaped to the processing system was 0.69% in 2016, which exceeds the median, estimated at 0.42%, as displayed in Figure 8.38. Several retention ponds are under construction to minimize the volume of untreated sewage. Furthermore, the adoption of stricter regulations for drainage will also reduce the untreated sewage spills. There are numerous factors that impact the estimated percentage of untreated sewage such as; (1) infrastructure age, where the age and condition of the sewer distribution network, as well as the maintenance frequency, contributes to the estimated percentage of sewage; (2) policies and maintenance practices, where the condition and types of maintenance equipment, as well as the network age, impact the estimated percentage of sewage; (3) treatment plants, where the size, number, and complexity of the treatment plants affect their performance and accordingly the estimated percentage of sewage; and (4) weather condition, where harsh impacts on the sewer pipes are associated with the frequent and severe climate conditions. The mathematical formulation of the untreated sewage could be displayed in Equation 8.10. Details about the variables could be displayed in Figure 8.39.

$$\text{Estimated percentage of untreated sewage} = \frac{Volume\ of\ untreated\ wastewater\ (mega\ liters)}{[Volume\ of\ untreated\ wastewater\ (mega\ liters) + Volume\ of\ treated\ sewage\ (mega\ liters)]} \quad (8.10)$$

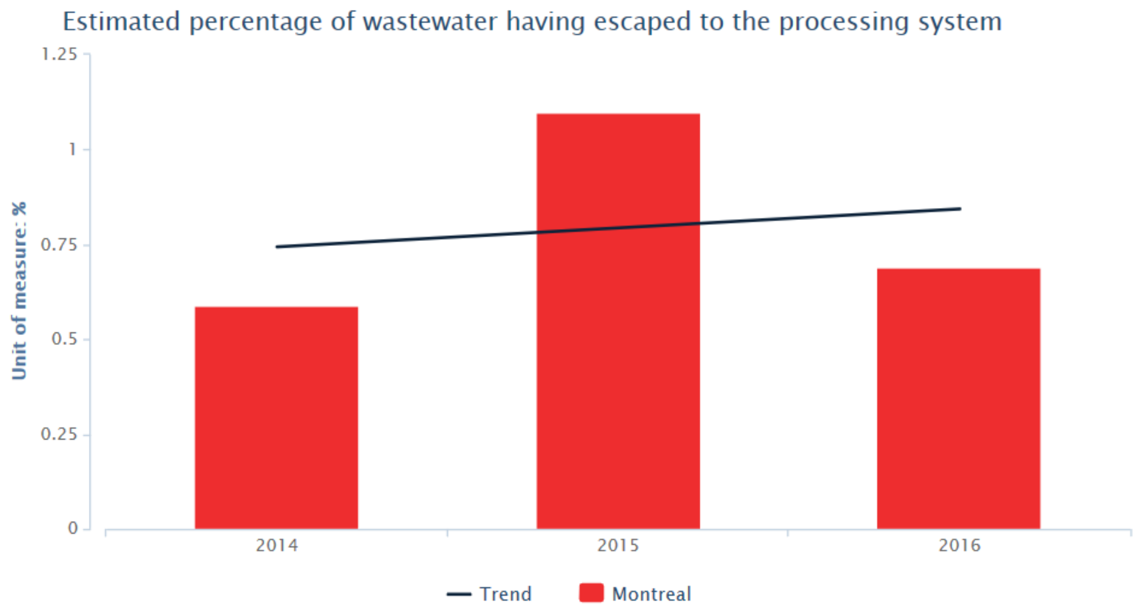


Figure 8.37: *Estimated percentage of wastewater having escaped to the processing system*

Table 8-18: *Analytical table for the estimated percentage of wastewater having escaped to the processing system*

	2014	2015	2016
Megalitres of sewage untreated	4 668	8 037	5 254
Megalitres of treated wastewater	785 358	723 296	751 711
Estimated percentage of wastewater having escaped to the processing system	0.59	1.10	0.69
Gap with previous year	-	86.4%	-37,3%
Evolution			16.9%

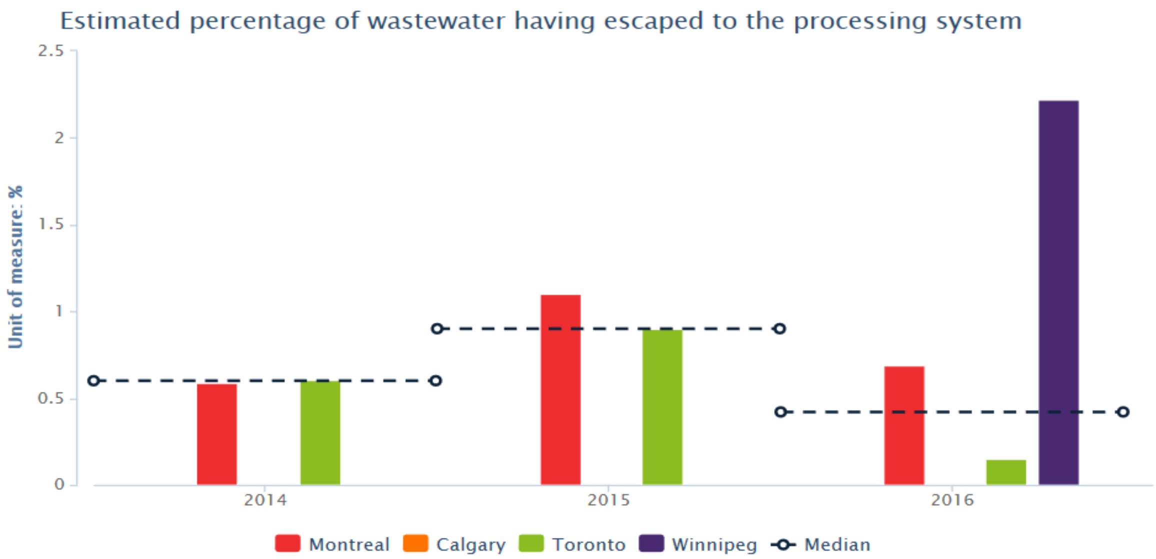


Figure 8.38: *Comparison of the estimated percentage of wastewater having escaped to the processing system among Canadian cities*

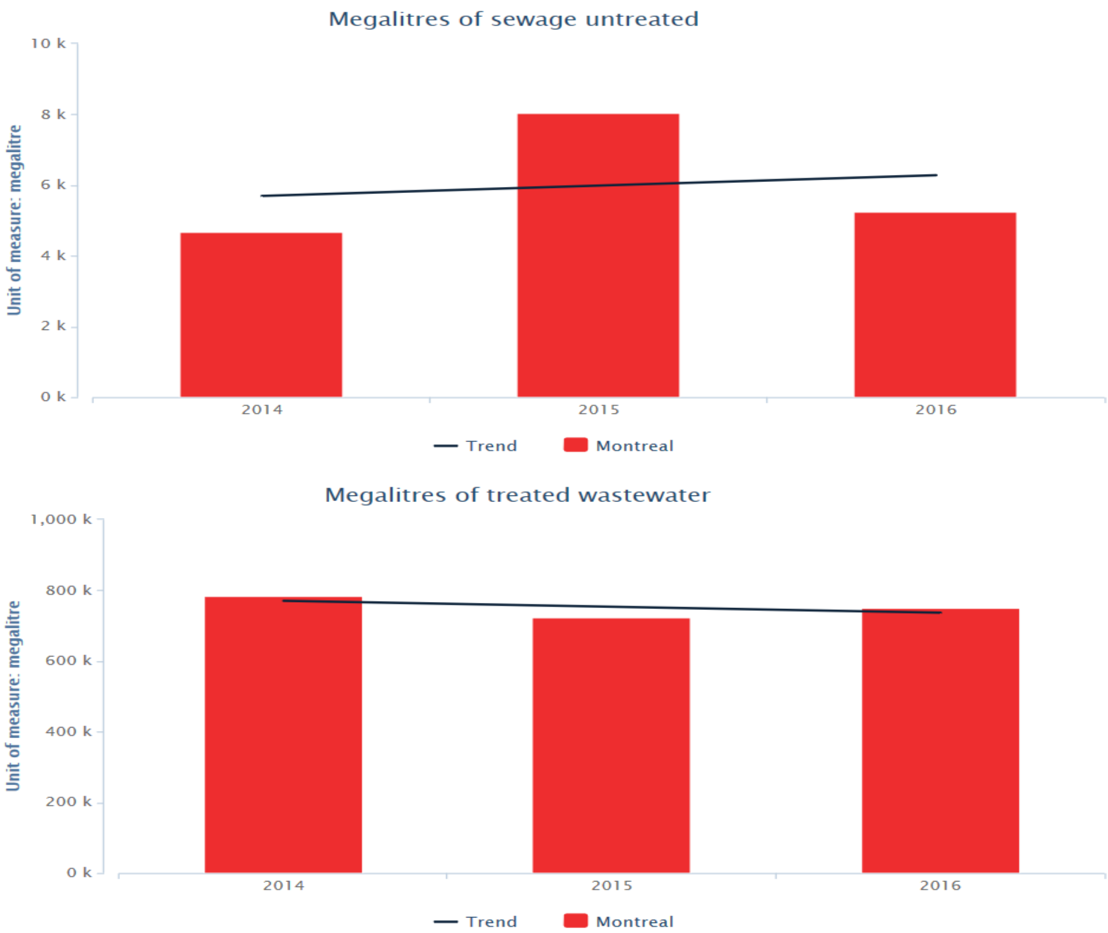


Figure 8.39: *Variables analysis for the estimated percentage of wastewater having escaped to the processing system*

8.2.3.4 *Financial*

The financial data was represented via three indicators: (1) cost of sewer system per kilometer of driving or per cubic meter of wastewater, (2) total cost of the transport/collection system of wastewater per kilometer of driving, and (3) total cost of the system of treatment and transport/collection of wastewater per megaliter. The 1st indicator considers the costs of the sewer operations (i.e. domestic, rain and unitary) such as; the maintenance of pumps and pipes; and cleaning of the sump. It covers the main and secondary sewer pipes network. Furthermore, it includes the depreciation expenses subtracted from the rendered services (i.e. income for the installation of sewer connection). Moreover, it includes indirect costs of administrative and technical support. The city of Montréal has one single sewage treatment plant and thus, several areas in the network carry relatively large volumes of wastewater over long distances as opposed to cities of the same size. Furthermore, the average age of the city of Montréal's combined sewer and wastewater network is 60.1 years and the cost of replacing a sewer pipe of the same diameter in high-density boroughs (i.e. downtown) costs around 70% to 80% more as opposed to other medium and low-density boroughs. As displayed in Figure 8.40 and Table 8-19, the cost increased by 6.7% between 2015 and 2016 because of the increased number of interventions in the secondary sewer network. Furthermore, the overall cost increased by 9.3% between 2012 and 2016, which is a result of the increased investment in cleaning, inspection, and maintenance of the sewer network to enhance its' condition state and reduce the maintenance deficit. The increased investments are reflected through the amortization costs, which increased by 23.3% between 2012 and 2016. Similarly, the cost per cubic meter of sewer system increased by 3.7% in 2016 as opposed to 2015, which is a result of the increased investment in cleaning, inspection, and maintenance of the sewer network to enhance its' condition state and reduce the maintenance deficit, as displayed in Figure 8.41. Furthermore, the cost per cubic meter of sewer system increased by 13.2% between 2012 and 2016 because of the increased number of interventions in the secondary sewer network. There are several factors that affect the cost of sewer system per kilometer of driving or per cubic meter of wastewater such as; network condition state; leak detection program; the number of overflows, obsolescence of the maintenance equipment; depreciated capital; population; topography; climate change; and economic development. The mathematical formulation of the cost of sewer system per kilometer of driving and per cubic meter of wastewater could be displayed in Equations 8.11 and 8.12 respectively. Details about the variables could be displayed in Figure 8.42 and Figure 8.43.

$$\text{Cost of sewer system per kilometer of driving} = \frac{\textit{Cost of sewer activities} - \textit{Sewer network services} + \textit{Depreciation of sewer network}}{\textit{Length of sewer network } (km)} \tag{8.11}$$

$$\text{Cost of sewer system per cubic meter of wastewater} = \frac{\textit{Cost of sewer activities} - \textit{Sewer network services} + \textit{Depreciation of sewer network}}{\textit{Volume of treated sewage } (m^3)} \tag{8.12}$$

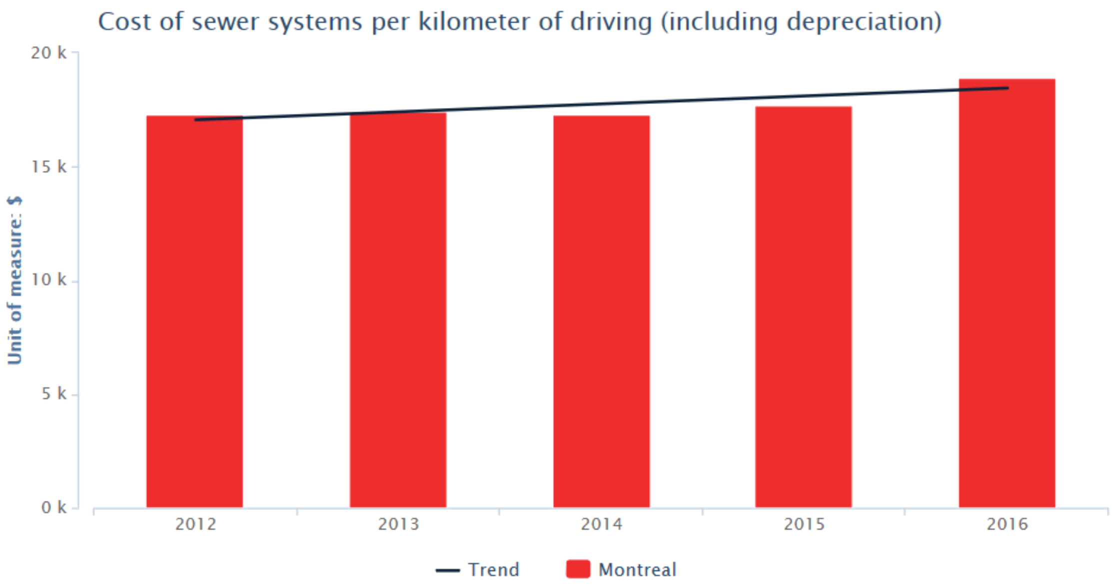


Figure 8.40: *Cost of sewer system per kilometer of driving*

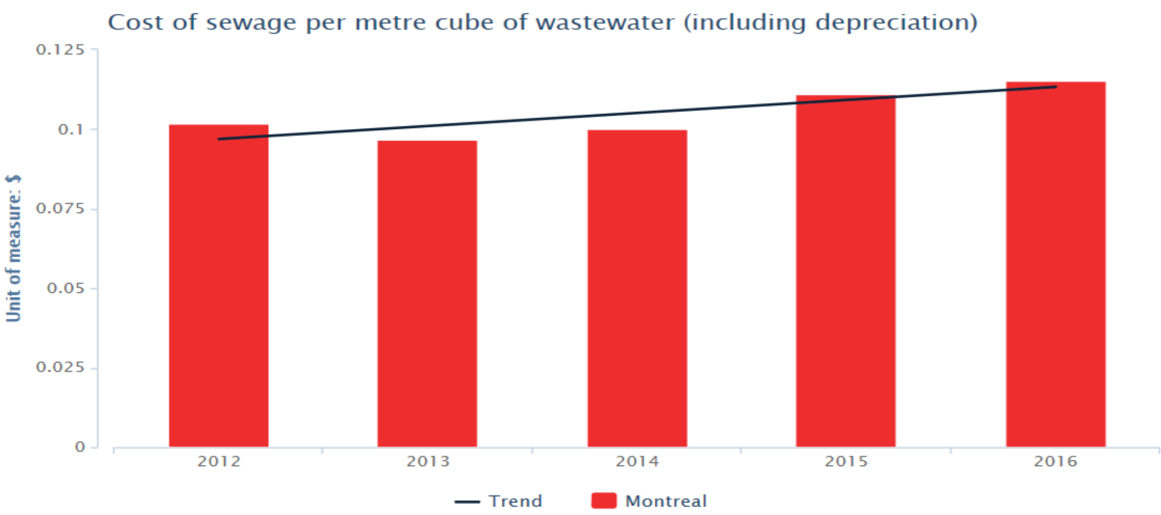


Figure 8.41: *Cost of sewer system per cubic meter of wastewater*

Table 8-19: *Analytical table for the cost of sewer system per kilometer of driving*

	2012	2013	2014	2015	2016
Cost of the activity of sewer systems (MAMOT)	38 874 000	37 191 000	36 914 000	37 037 000	40 996 000
Services related to sewer systems (MAMOT)	573 000	458 958	333 000	544 000	695 000
Amortization of sewer systems (MAMOT)	45 132 000	47 404 000	50 487 000	52 614 000	55 642 000
Number of kilometres of sewer line	4 816	4 816	5 024	5 024	5 068
Cost of sewer systems per kilometer of driving (including depreciation)	17 324	17 470	17 330	17 736	18 931
Gap with previous year	-	0.8%	-0.8%	2.3%	6.7%
Evolution					9.3%

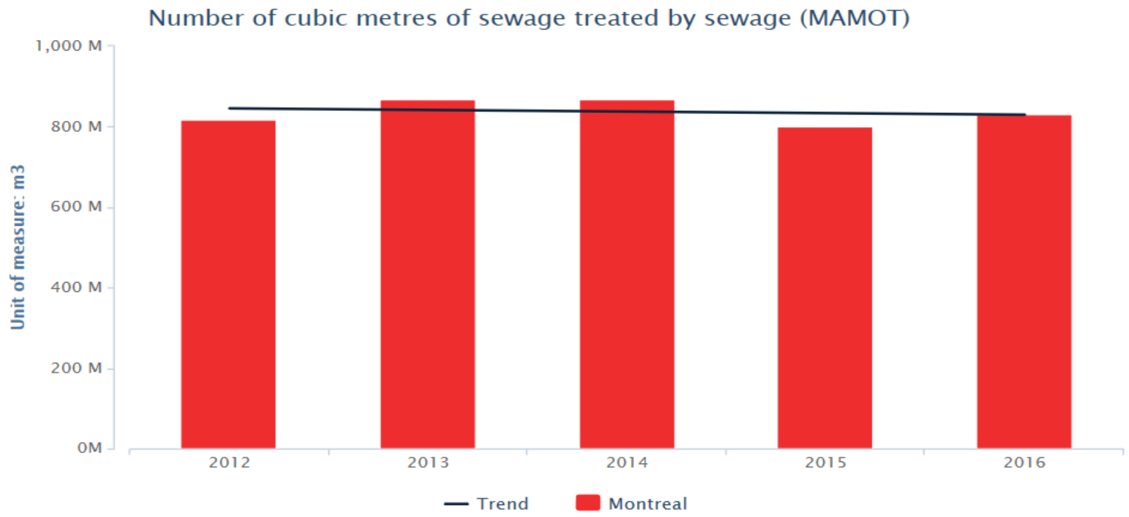


Figure 8.42: *Volume of treated sewage*

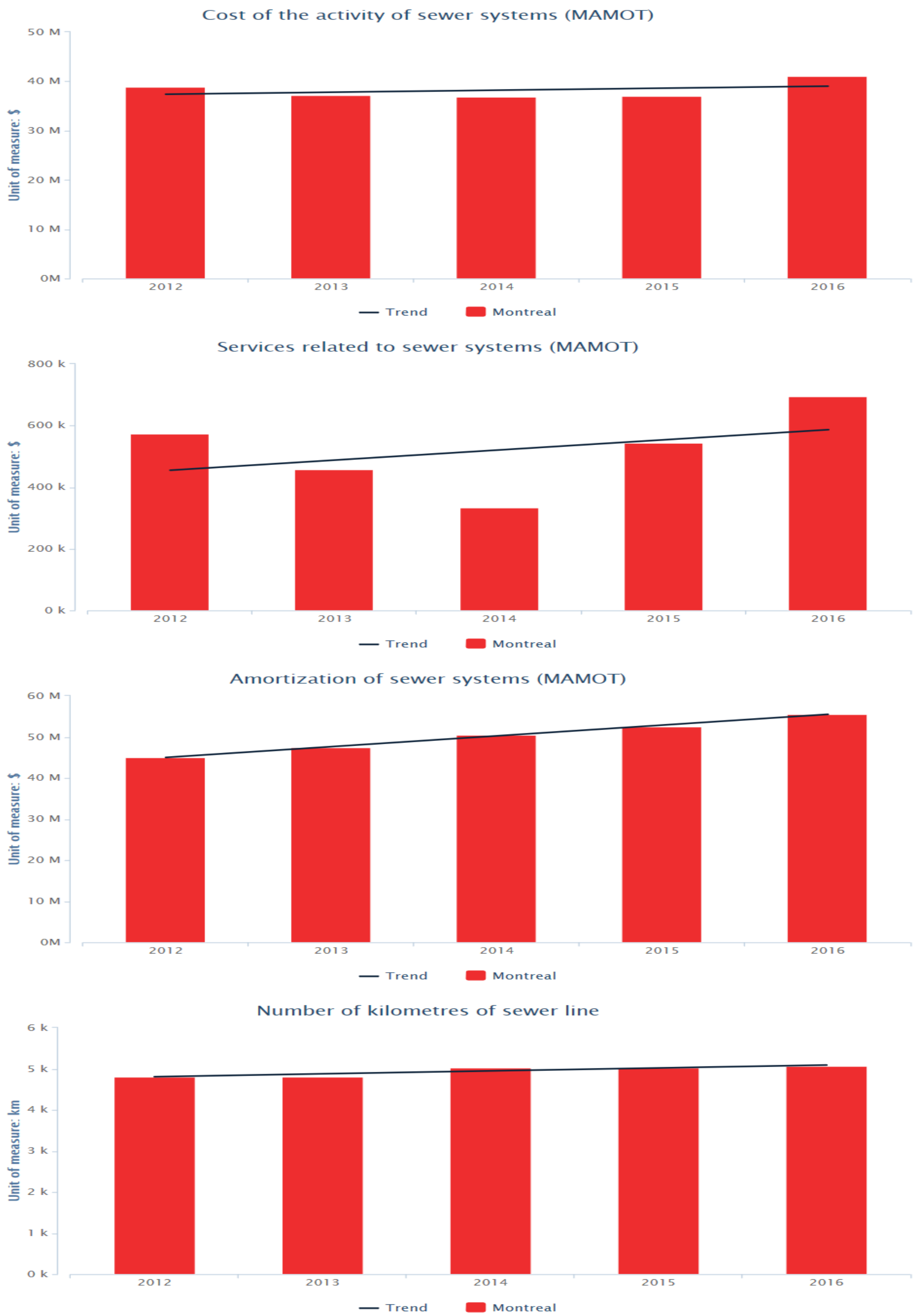


Figure 8.43: *Variables analysis for the cost of sewer system per kilometer of driving*

The 2nd indicator considers the cost of the sanitary sewer operations such as; pumps and ducts maintenance and sumps' cleaning. The compilation of the network length includes the main and secondary sewer pipe networks and excludes the service connections. Furthermore, the cost includes the depreciation expenses as well as support activities. Moreover, it includes the indirect institutional expenditures such as; budget management, accounting, management of human resources, purchasing, inventory management, information technology, legal services, etc. As displayed in Figure 8.44 and Table **8-20**, the total cost of the transport/collection system of wastewater per kilometer of driving increased by 7.2% in 2016 as opposed to 2015. This increase is a result of boosting the investments in the maintenance of the secondary sewer lines. It should be noted that depreciation represents more than half the activity cost, given the fact that the renewal rate remains greater than 1.2%. In summary, the total cost of the transport/collection system of wastewater per kilometer of driving increased by 12.3% between 2012 and 2016, which indicates the municipalities are in a catch-up phase to enhance the network condition state and reduce the maintenance deficit. However, the number of interventions will return to its' normal level in the near future, after enhancing the overall network condition state. Similarly, Figure 8.45 and Table 8-21 displayed the same trend of Figure 8.44 and Table **8-20**, but excluding depreciation.

On a global scale, the city of Montréal displayed higher costs in 2016 as opposed to the median of the cities, where the city of Montréal costs were estimated at $20,239 as opposed to a median of $17,872, with $2,367 difference above the median, as shown in Figure 8.46. This gap is linked to the network condition state and the rehabilitation efforts, which varies from one city to another. Furthermore, the population density, capitalization and amortization of capital spending policies impact the total costs. The city of Montréal depreciates its infrastructure over a period of 20 to 40 years, depending on whether it is rehabilitation or reconstruction. The longer period of capitalization reduces the annual operational costs of the network. After excluding the amortization, the city of Montréal displayed fewer costs below the median as displayed in Figure 8.47. There are numerous factors that impact the total cost of transport/collection of wastewater per kilometer of driving such as; (1) amortization, where the amortization costs vary among the municipalities according to the length of the infrastructure useful life, investment in capital programs, and capitalization policy; (2) infrastructure age, where the age and condition of the sewer distribution network as well as the pipe materials and maintenance frequency contribute to the total cost of transport/collection of wastewater; (3) urban density, where the proximity of the lines to other facilities increases the repair and replacement costs; (4) government management structure, where the government structure (i.e. one level of governance vs several levels of governance, where the responsibility is shared among the borough municipalities) influence the total cost of transport/collection of wastewater; (5) policies and maintenance practices, where the condition and types of maintenance equipment, as well as the network age, impact the total cost of transport/collection of wastewater; and (6) weather condition, where harsh impacts on the sewer pipes are associated with the frequent and severe climate conditions. The mathematical formulation of the total cost of transport/collection of wastewater per kilometer of driving could be displayed in Equation 8.13. Details about the variables could be displayed in Figure 8.48.

$$\text{Total cost of transport/collection of wastewater per kilometer of driving} = \frac{Direct\ costs + Support\ costs + Depreciation\ of\ sewer\ network - Income\ from\ other\ municipalities}{Length\ of\ pipes\ transport/collection\ of\ wastewater\ system\ (km)} \tag{8.13}$$

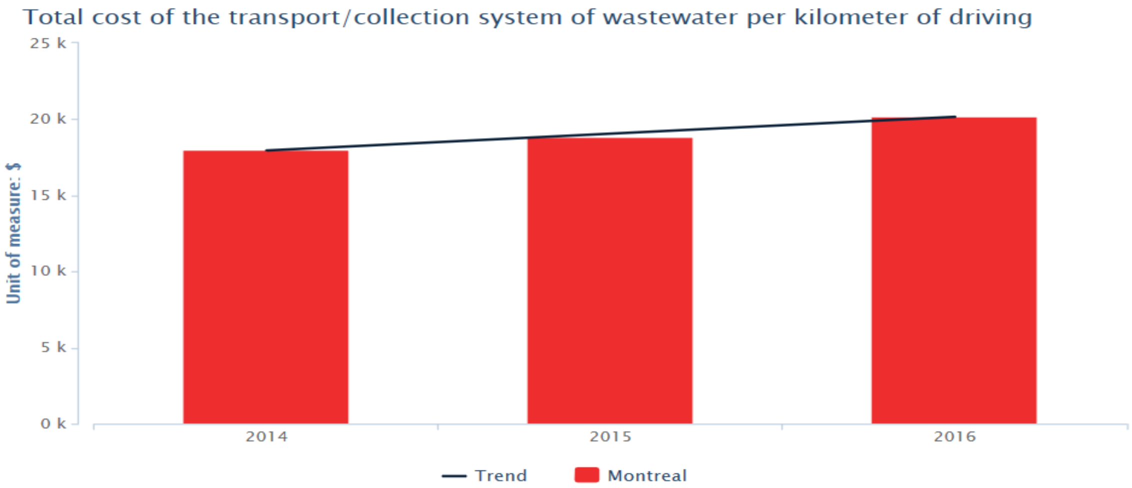


Figure 8.44: *Total cost of the transport/collection system of wastewater per kilometer of driving*

Table 8-20: *Analytical table for the total cost of the transport/collection system of wastewater per kilometer of driving*

	2014	2015	2016
Direct costs related to the sanitary sewer system	29 055 052	29 395 099	32 514 725
Support costs of the activities related to the sanitary sewer	5 172 624	6 409 674	6 630 839
Depreciation relative to the sanitary sewer system	40 057 370	42 071 329	44 324 474
Income from other municipalities related to the sanitary sewer system	0	0	0
Length in km of pipes to transport/collection of wastewater system	4 121	4 123	4 124
Total cost of the transport/collection system of wastewater per kilometer of driving	18 026	18 888	20 239
Gap with previous year	-	4.8%	7.2%
Evolution			12.3%

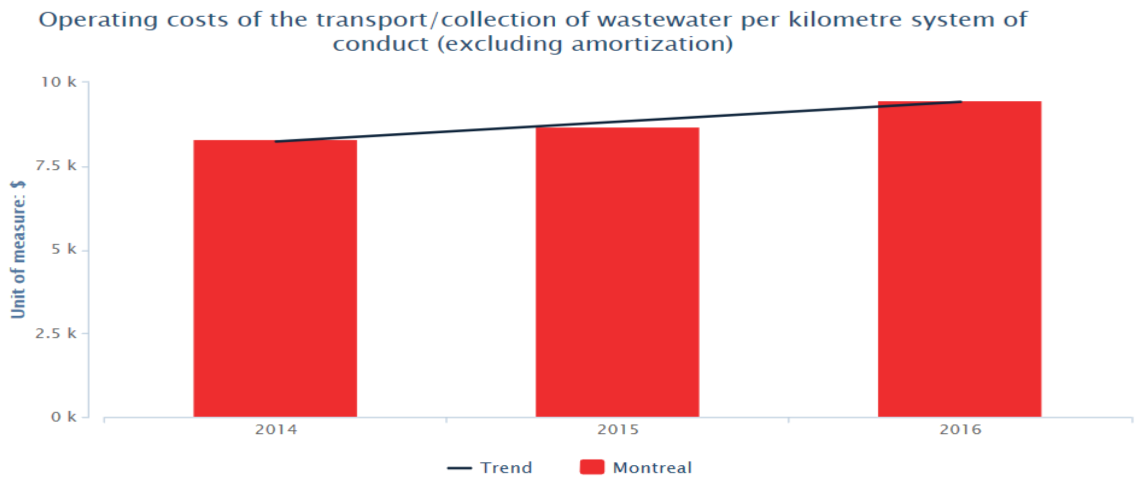


Figure 8.45: *Total cost of the transport/collection system of wastewater per kilometer of driving (excluding amortization)*

Table 8-21: *Analytical table for the total cost of the transport/collection system of wastewater per kilometer of driving (excluding amortization)*

	2014	2015	2016
Operating costs of the transport/collection system of waste water per kilometre of conduct (excluding amortization)	8 306	8 684	9 492
Gap with previous year	-	4.6%	9.3%
Evolution			14.3%

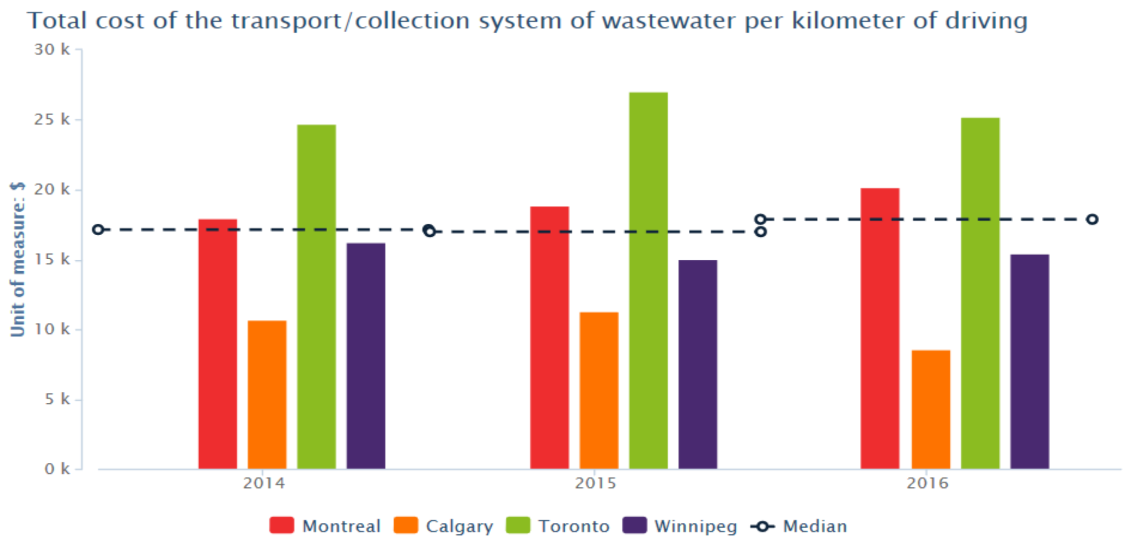


Figure 8.46: *Comparison of the total cost of the transport/collection system of wastewater per kilometer of driving among Canadian cities*

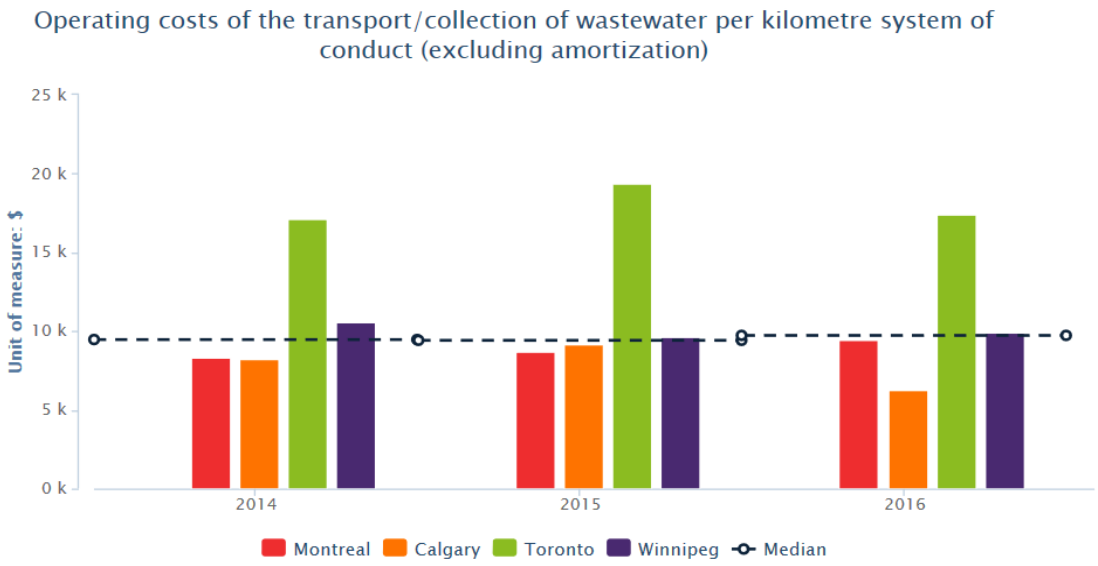


Figure 8.47: *Comparison of the total cost of the transport/collection system of wastewater per kilometer of driving among Canadian cities (excluding amortization)*

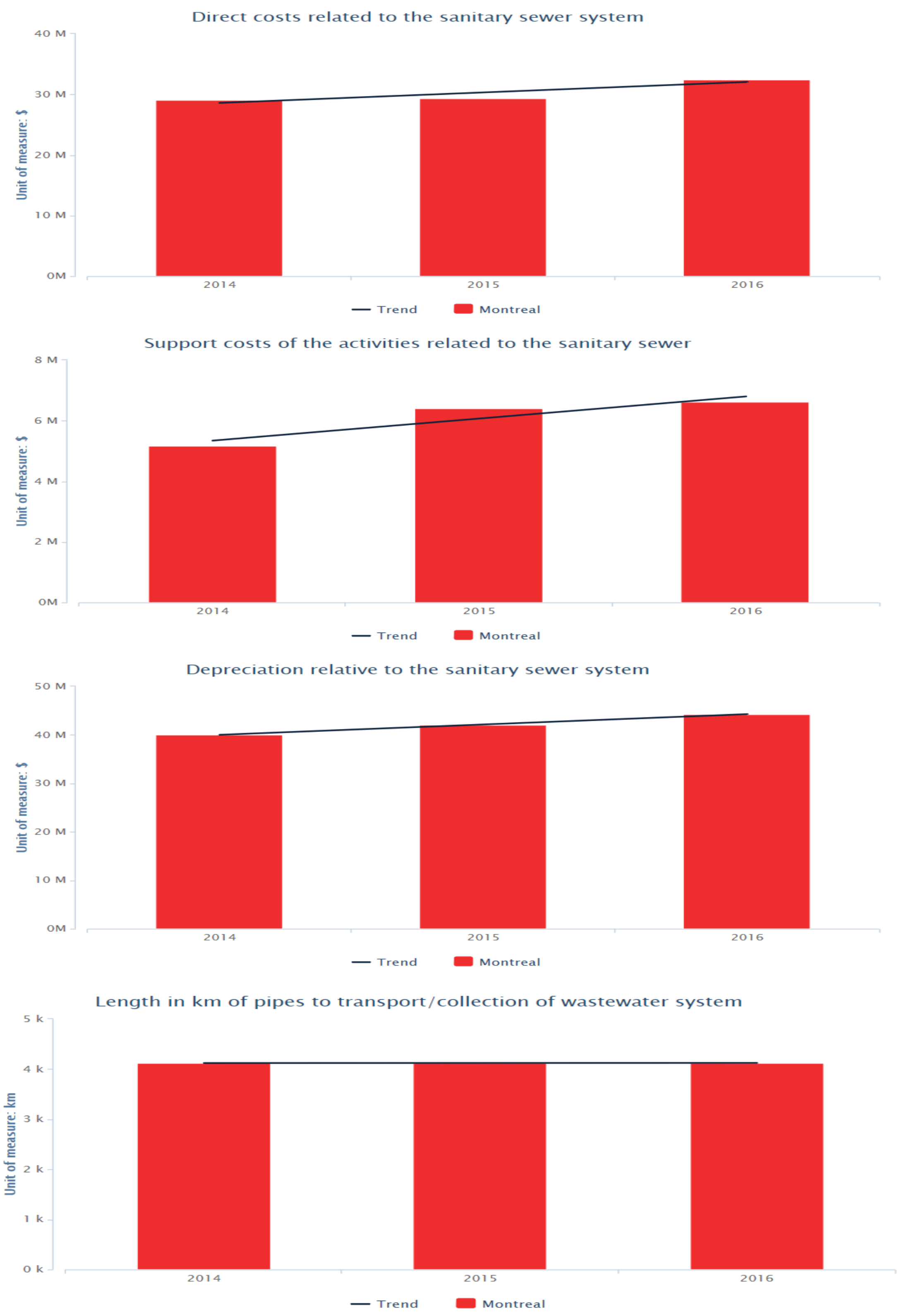


Figure 8.48: *Variables analysis for the total cost of the transport/collection system of wastewater per kilometer of driving*

The 3rd indicator considers the operations of wastewater treatment (i.e. maintenance, repair and operation of the stations, purification and retention basins) and operations of the sanitary sewer (i.e. pumps and ducts maintenance and sumps' cleaning). It covers the total volume of wastewater captured by main and secondary sewer networks. Furthermore, it includes the depreciation expenses as well as support activities. Moreover, it includes the indirect institutional expenditures such as; budget management, accounting, management of human resources, purchasing, inventory management, information technology, legal services, etc. As displayed in Figure 8.49 and Table 8-22, the total cost of the transport/collection system of wastewater per megaliter remained stable between 2015 and 2016 because the increase in the costs was coupled with a 3.9% increase in the volume of treated sewage. Furthermore, the total cost of the transport/collection system of wastewater per megaliter increased by 12.6% between 2014 and 2016. This increase was mainly due to the 4.3% reduction in the volume of wastewater received at the wastewater treatment plant from 758,358 megaliters in 2014 to 751,711 megaliters in 2016. Similarly, Figure 8.50 and Table 8-23 displayed the same trend in Figure 8.49 and Table 8-22, but excluding depreciation.

On a global scale, the city of Montréal displayed $662 less in terms of wastewater treatment and transport/collection system per megaliter as opposed to the median in 2016, where the city of Montréal displayed $263.92 as opposed to a median of $926.32, as displayed in Figure 8.51. Similarly, Figure 8.52 displayed the same trend as Figure 8.51, but excluding depreciation. It is worth noting that the city of Montréal wastewater treatment plant treats nearly 2,500 megaliters of sewage in normal days and up to 8,000 megaliters in rainy days, given that the network is unitary at 80%. In terms of volume, the city of Montréal wastewater network represents nearly 50% of Québec's wastewater. The reason behind this huge volume is the fact that Montréal serves large population that is coupled with a high percentage of industrial, commercial, and institutional users. This resulted in an increased volume of wastewater treated per capita, three times higher than other cities. The city of Montréal produces the wastewater at a competitive cost as opposed to other cities because of those factors: (1) the low material concentration in the wastewater, especially in periods of heavy rain, given that the city of Montréal uses a unitary network for collecting the sewer and rain; and (2) economy of scale given the fact that Montréal serves a population of nearly 2 million citizens. There are numerous factors that impact the total cost of transport/collection of wastewater per megaliter such as; (1) amortization, where the amortization costs vary among the municipalities according to the length of the infrastructure useful life, investment in capital programs, and capitalization policy; (2) infrastructure age, where the age and condition of the sewer distribution network as well as the pipe materials and maintenance frequency contribute to the total cost of transport/collection of wastewater; (3) urban density, where the proximity of the lines to other facilities increases the repair and replacement costs; (4) government management structure, where the government structure (i.e. one level of governance vs several levels of governance, where the responsibility is shared among the borough municipalities) influence the total cost of transport/collection of wastewater; (5) policies and maintenance practices, where the condition and types of maintenance equipment, as well as the network age, impact the total cost of transport/collection of wastewater; (6) treatment plant, where the number, size, and technology of the treatment plants impact the total cost of transport/collection of wastewater; (7) supply and demand, where the total cost of transport/collection of wastewater is impacted by the total demand of the system as well as the division of the sewer among residential, industrial, commercial, and institutional sectors; and (8) weather condition, where harsh impacts on the sewer pipes are associated with the frequent and severe climate conditions. The mathematical formulation of the total cost of transport/collection of wastewater per megaliter could be displayed in Equation 8.14. Details about the variables could be displayed in Figure 8.53 and Figure 8.54.

$$\text{Total cost of the transport/collection system of wastewater per megaliter} = \frac{\textit{Direct costs} + \textit{Support costs} + \textit{Depreciation of sewer network} - \textit{Income from other municipalities}}{\textit{Volume of treated sewage (mega liters)}} \tag{8.14}$$

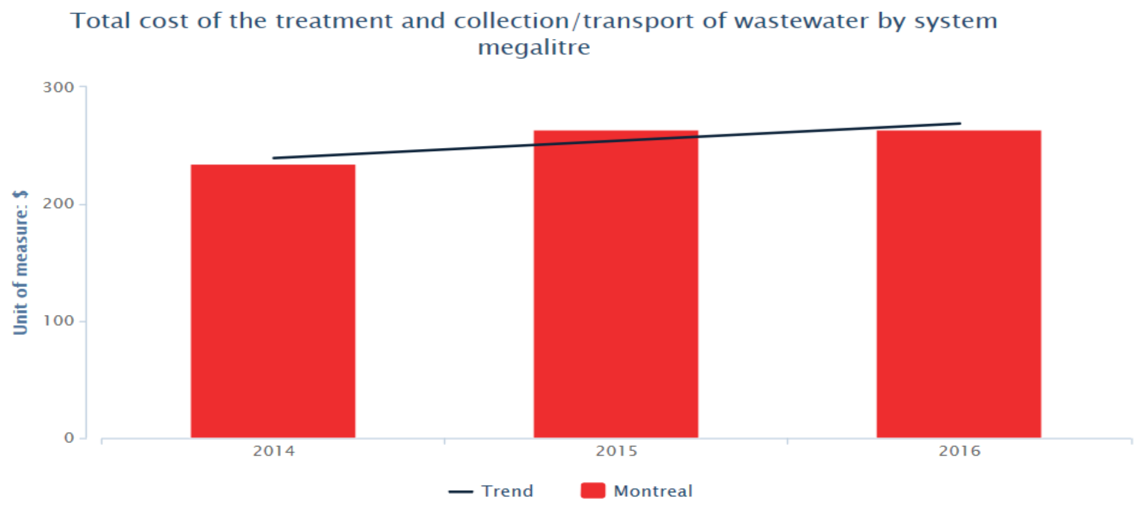


Figure 8.49: *Total cost of the transport/collection system of wastewater per megaliter*

Table 8-22: *Analytical table for the total cost of the transport/collection system of wastewater per megaliter*

	2014	2015	2016
Direct costs related to the sanitary sewer system	29 055 052	29 395 099	32 514 725
Support costs of the activities related to the sanitary sewer	5 172 624	6 409 674	6 630 839
Depreciation relative to the sanitary sewer system	40 057 370	42 071 329	44 324 474
Income from other municipalities related to the sanitary sewer system	0	0	0
Direct costs related to the treatment of wastewater	48 407 693	49 667 939	51 068 579
Support costs of the activities related to the treatment of wastewater	5 620 810	7 429 093	7 156 302
Depreciation on the treatment of wastewater	55 774 523	55 881 120	56 698 086
Income from other municipalities related to treatment of wastewater	0	0	0
Megalitres of treated wastewater	785 358	723 296	751 711
Total cost of the system of treatment and transport/collection of wastewater per megalitre	234,40	263,87	263,92
Gap with previous year	-	12.6%	0,0%
Evolution			12.6%

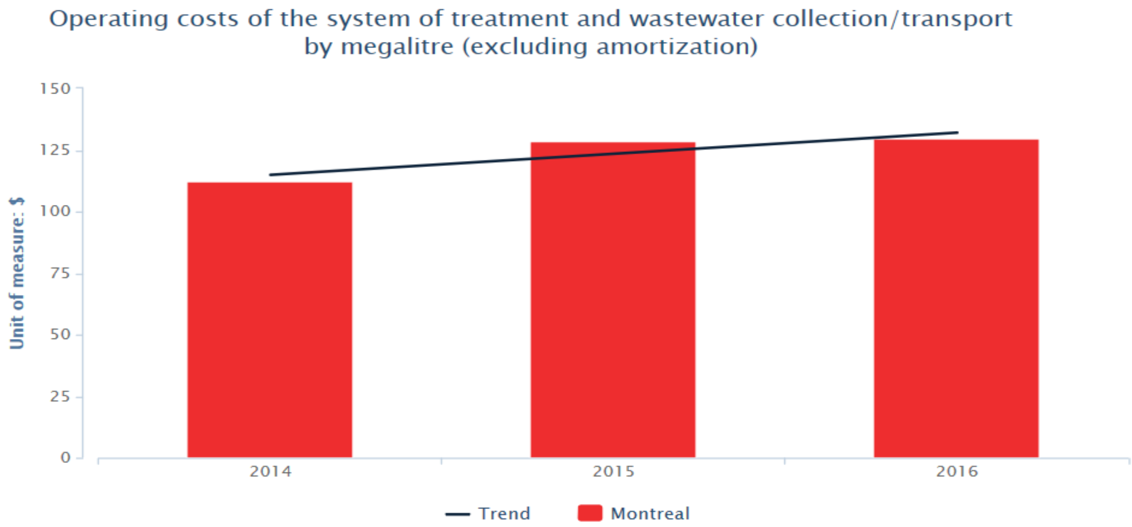


Figure 8.50: *Total cost of the transport/collection system of wastewater per megaliter (excluding amortization)*

Table 8-23: *Analytical table for the total cost of the transport/collection system of wastewater per megaliter (excluding amortization)*

	2014	2015	2016
Operating costs of the system of treatment and transport/collection of wastewater per megalitre (excluding amortization)	112,38	128,44	129,53
Gap with previous year	-	14.3%	0.8%
Evolution			15.3%

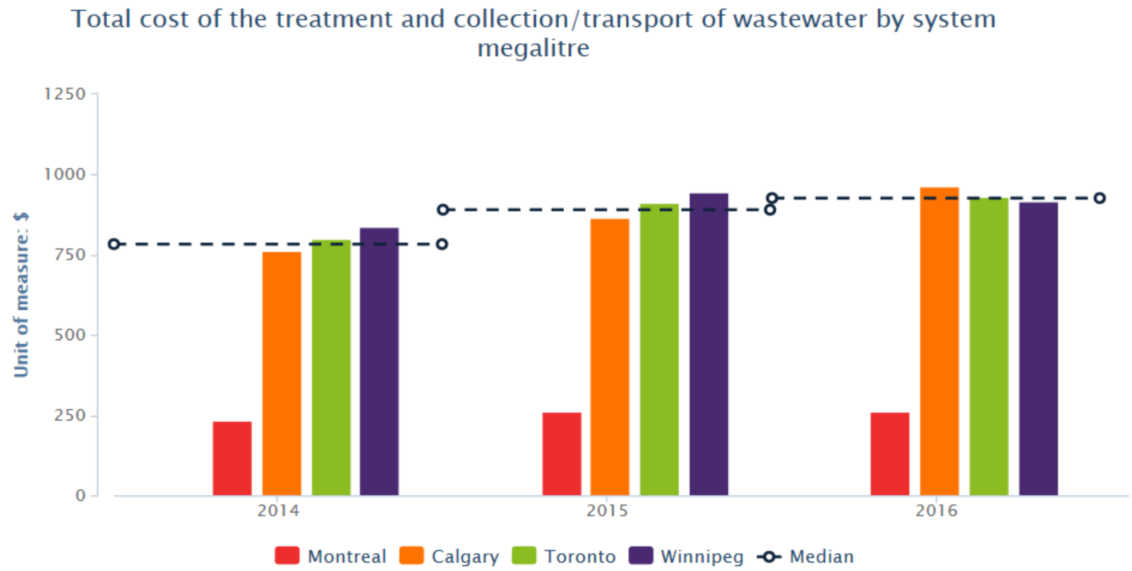


Figure 8.51: *Comparison of the total cost of the transport/collection system of wastewater per megaliter among Canadian cities*

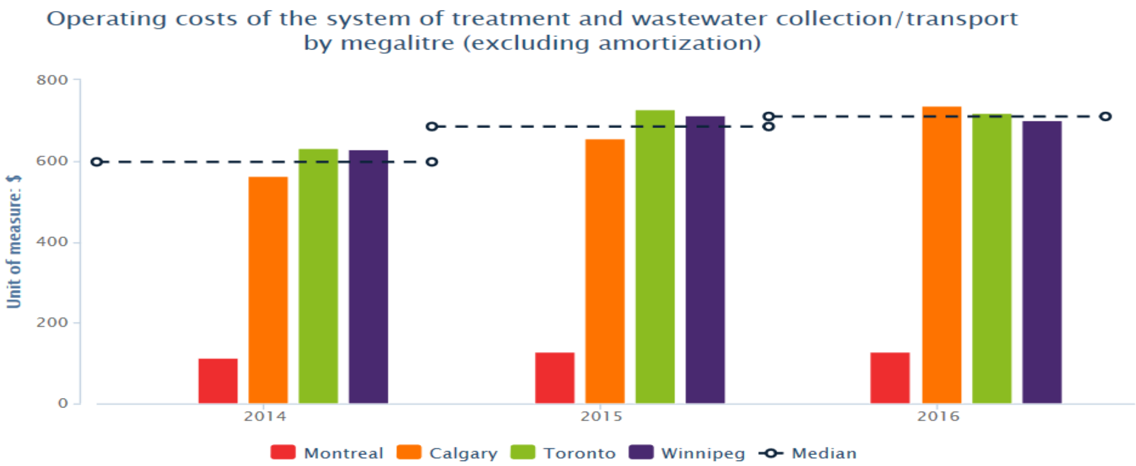


Figure 8.52: *Comparison of the total cost of the transport/collection system of wastewater per megaliter among Canadian cities (excluding amortization)*

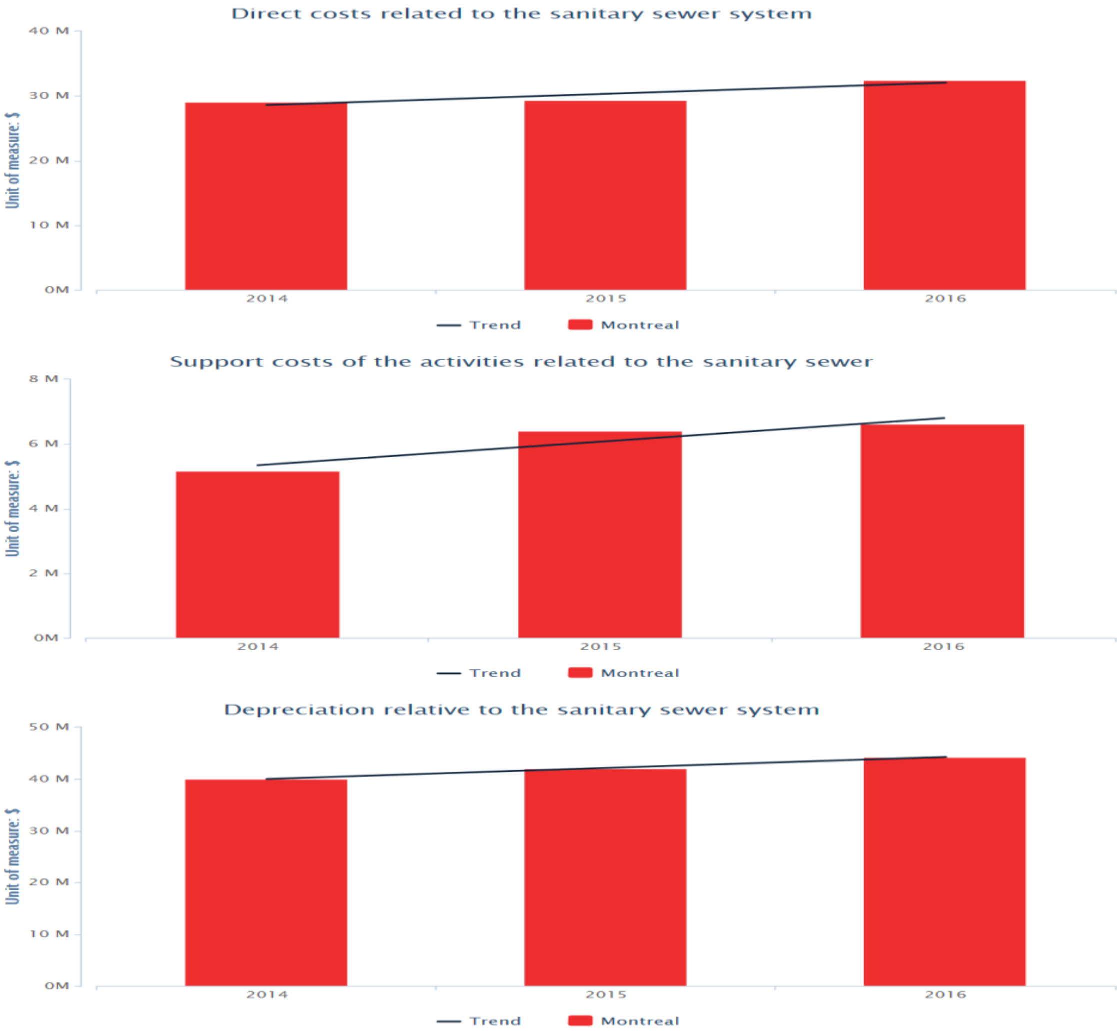


Figure 8.53: *Variables analysis for the total cost of the transport/collection system of wastewater per megaliter (1 out of 2)*

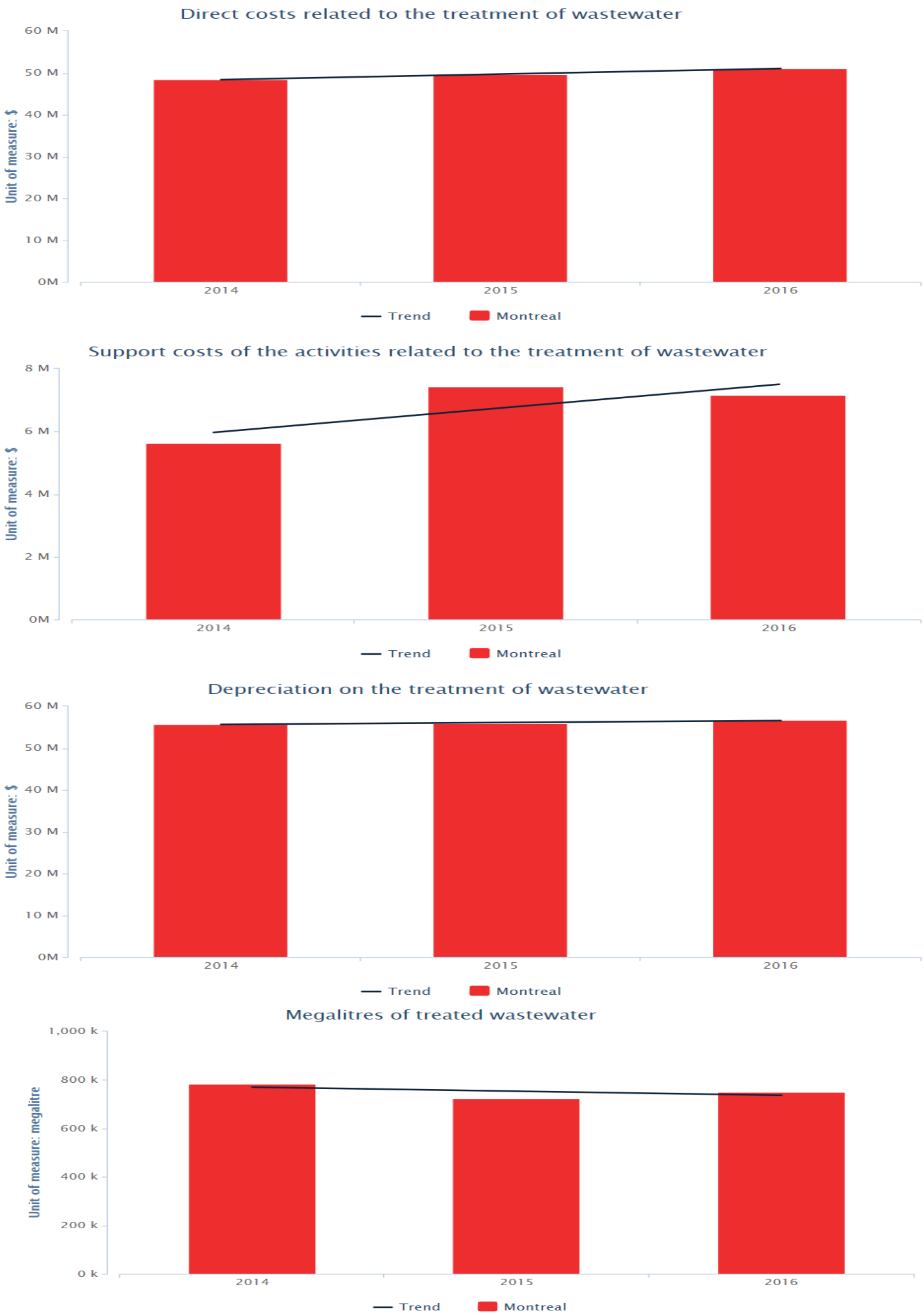


Figure 8.54: *Variables analysis for the total cost of the transport/collection system of wastewater per megaliter (2 out of 2)*

8.3 Appendix C: Town of Kindersley Case Study

8.3.1 *Roads Network*

Table 8-24: *Town of Kindersley roads' network*

Corridor ID#	Road type	Road structural design	Traffic	Corridor length	Roads age
1	Gravel	Weak	Light	230	18
2	Gravel	Weak	Light	245	18
3	Road	Weak	Light	117	1
4	Road	Weak	Light	111	7
5	Road	Strong	Medium	185	5
6	Road	Weak	Light	108	7
7	Road	Weak	Light	77	9
8	Road	Strong	Light	120	1
9	Gravel	Weak	Light	20	18
10	Gravel	Weak	Light	253	18
11	Gravel	Weak	Light	32	18
12	Gravel	Weak	Light	255	18
13	Gravel	Weak	Light	256	18
14	Road	Weak	Light	103	1
15	Road	Weak	Light	104	7
16	Road	Weak	Light	137	7
17	Road	Weak	Light	140	7
18	Road	Weak	Medium	115	9
19	Road	Weak	Light	143	7
20	Road	Weak	Light	1	8
21	Road	Strong	Medium	186	5
22	Road	Weak	Light	205	7
23	Road	Strong	Medium	101	5
24	Road	Weak	Light	133	3
25	Road	Weak	Light	95	7
26	Road	Weak	Light	89	11
27	Road	Weak	Light	110	1
28	Road	Weak	Light	83	3
29	Road	Weak	Light	106	3
30	Road	Weak	Light	86	11
31	Road	Strong	Light	81	3
32	Road	Weak	Light	142	7
33	Road	Weak	Light	126	16
34	Road	Weak	Light	76	9
35	Road	Strong	Light	37	1
36	Road	Weak	Light	127	7
37	Road	Weak	Light	121	13
38	Road	Weak	Light	123	15
39	Road	Weak	Light	136	13

Corridor ID#	Road type	Road structural design	Traffic	Corridor length	Roads age
40	Road	Weak	Light	124	11
41	Road	Weak	Light	125	7
42	Road	Weak	Light	148	7
43	Road	Weak	Light	68	7
44	Road	Strong	Light	55	9
45	Gravel	Weak	Light	34	18
46	Road	Weak	Light	197	9
47	Road	Weak	Light	153	11
48	Road	Weak	Light	174	10
49	Road	Strong	Light	210	1
50	Road	Weak	Light	158	11
51	Road	Weak	Light	164	13
52	Road	Weak	Light	228	18
53	Gravel	Weak	Light	226	18
54	Road	Weak	Light	64	18
55	Road	Strong	Light	176	7
56	Road	Strong	Light	47	7
57	Road	Strong	Light	177	7
58	Road	Strong	Medium	5	7
59	Road	Strong	Light	52	13
60	Road	Strong	Light	171	7
61	Gravel	Weak	Light	265	18
62	Gravel	Weak	Light	232	18
63	Road	Weak	Light	222	18
64	Road	Weak	Light	221	18
65	Road	Weak	Light	27	18
66	Gravel	Weak	Light	33	18
67	Gravel	Weak	Light	243	18
68	Gravel	Weak	Light	241	18
69	Gravel	Weak	Light	244	18
70	Gravel	Weak	Light	258	18
71	Gravel	Weak	Light	214	18
72	Gravel	Weak	Medium	216	18
73	Gravel	Weak	Light	21	18
74	Road	Strong	Light	162	15
75	Road	Weak	Light	201	18
76	Road	Strong	Light	179	3
77	Gravel	Weak	Light	259	18
78	Road	Strong	Light	61	9
79	Road	Weak	Light	206	3
80	Road	Weak	Light	112	9
81	Road	Weak	Light	116	7
82	Road	Strong	Medium	188	5
83	Road	Weak	Light	118	3

Corridor ID#	Road type	Road structural design	Traffic	Corridor length	Roads age
84	Road	Weak	Light	113	7
85	Road	Weak	Light	107	1
86	Road	Weak	Light	109	7
87	Road	Weak	Light	13	1
88	Road	Weak	Light	134	3
89	Road	Strong	Light	128	1
90	Road	Weak	Light	130	13
91	Road	Weak	Medium	215	25
92	Road	Weak	Light	131	3
93	Road	Strong	Light	129	1
94	Road	Strong	Light	93	5
95	Road	Strong	Light	94	5
96	Road	Weak	Light	90	7
97	Road	Weak	Light	84	7
98	Road	Weak	Light	88	3
99	Road	Weak	Light	91	7
100	Road	Weak	Light	96	15
101	Road	Weak	Light	102	7
102	Road	Weak	Light	138	7
103	Road	Weak	Light	135	1
104	Road	Weak	Light	194	16
105	Road	Strong	Light	40	5
106	Road	Weak	Light	78	15
107	Road	Weak	Light	49	16
108	Road	Strong	Light	75	13
109	Road	Weak	Light	139	13
110	Road	Weak	Light	149	11
111	Road	Weak	Light	69	3
112	Road	Weak	Light	150	7
113	Road	Weak	Light	45	7
114	Road	Weak	Light	46	1
115	Road	Strong	Medium	189	5
116	Road	Weak	Light	70	3
117	Road	Weak	Light	147	3
118	Road	Weak	Light	207	3
119	Road	Weak	Light	190	1
120	Road	Weak	Light	168	15
121	Road	Weak	Light	154	1
122	Road	Strong	Medium	169	5
123	Road	Strong	High	159	9
124	Road	Weak	Light	262	18
125	Road	Strong	High	199	9
126	Road	Strong	High	167	9

8.3.2 *Sewer network*

Table 8-25: *Town of Kindersley sewer network*

Corridor ID#	Sewer/Storm pipes	Sewer pipes types	Sewer Pipe diameter	Sewer pipe age	Sewer excavation depth	Corridor length	Sewer demand category	Sewer demand age
1	Combined	Pvc	S10	26	15	230	Low	26
2	Combined	Pvc	S8	26	15	245	Low	26
3	Combined	Conc	S15	44	15	117	Medium	44
4	Combined	Conc	S21	46	15	111	High	46
5	Combined	Conc	S8	46	15	185	Medium	46
6	Combined	Conc	S21	46	15	108	Medium	46
7	Combined	Conc	S18	44	15	77	High	44
8	Combined	Conc	S18	44	15	120	Low	44
9	Combined	Pvc	S8	12	15	20	Medium	12
10	Combined	Pvc	S6	27	15	253	High	27
11	Combined	Pvc	S8	6	15	32	Low	6
12	Combined	Conc	S8	35	15	255	Low	35
13	Combined	Pvc	S8	35	15	256	Medium	35
14	Combined	Conc	S24	46	15	103	High	46
15	Combined	Conc	S21	46	15	104	Medium	46
16	Combined	Conc	S15	46	15	137	Medium	46
17	Combined	Conc	S15	45	15	140	High	45
18	Combined	Conc	S18	45	15	115	Low	45
19	Combined	Vct	S12	44	15	143	Medium	44
20	Combined	Pvc	S8	44	15	1	High	44
21	Combined	Ac	S8	46	15	186	High	46
22	Combined	Conc	S10	60	15	205	Low	60
23	Combined	Conc	S30	46	15	101	Low	46
24	Combined	Conc	S15	46	15	133	Medium	46
25	Combined	Conc	S15	44	15	95	High	44
26	Combined	Conc	S15	44	15	89	Medium	44
27	Combined	Conc	S21	46	15	110	Medium	46
28	Combined	Conc	S18	44	15	83	High	44
29	Combined	Conc	S18	46	15	106	Low	46
30	Combined	Conc	S24	44	15	86	Medium	44
31	Combined	Conc	S24	44	15	81	High	44
32	Combined	Vct	S12	44	15	142	High	44
33	Combined	Conc	S15	44	15	126	Low	44
34	Combined	Conc	S21	44	15	76	Low	44
35	Combined	Pvc	S8	27	15	37	Medium	27
36	Combined	Conc	S15	44	15	127	High	44
37	Combined	Vct	S12	44	15	121	Medium	44
38	Combined	Vct	S12	44	15	123	Medium	44
39	Combined	Vct	S12	44	15	136	High	44
40	Combined	Vct	S12	44	15	124	Low	44

Corridor ID#	Sewer/Storm pipes	Sewer pipes types	Sewer Pipe diameter	Sewer pipe age	Sewer excavation depth	Corridor length	Sewer demand category	Sewer demand age
41	Combined	Vct	S12	44	15	125	Medium	44
42	Combined	Vct	S12	44	15	148	High	44
43	Combined	Pvc	S12	20	15	68	High	20
44	Combined	Vct	S8	46	15	55	Low	46
45	Combined	Pvc	S8	27	15	34	Low	27
46	Combined	Conc	S8	44	15	197	Medium	44
47	Combined	Vct	S10	44	15	153	High	44
48	Combined	Conc	S12	44	15	174	Medium	44
49	Combined	Vct	S8	60	15	210	Medium	60
50	Combined	Conc	S15	44	15	158	High	44
51	Combined	Vct	S12	44	15	164	Low	44
52	Combined	Vct	S8	40	15	228	Medium	40
53	Combined	Vct	S8	40	15	226	High	40
54	Combined	Pvc	S10	20	15	64	High	20
55	Combined	Pvc	S18	25	15	176	Low	25
56	Combined	Ac	S8	28	15	47	Low	28
57	Combined	Pvc	S18	25	15	177	Medium	25
58	Combined	Pvc	S10	2	15	5	High	2
59	Combined	Pvc	S18	25	15	52	Medium	25
60	Combined	Vct	S18	25	15	171	Medium	25
61	Combined	Pvc	S10	26	15	265	High	26
62	Combined	Pvc	S10	26	15	232	Low	26
63	Combined	Vct	S8	50	15	222	Medium	50
64	Combined	Conc	S8	50	15	221	High	50
65	Combined	Pvc	S8	40	15	27	High	40
66	Combined	Pvc	S8	6	15	33	Low	6
67	Combined	Pvc	S8	26	15	243	Low	26
68	Combined	Pvc	S8	26	15	241	Medium	26
69	Combined	Ac	S8	26	15	244	High	26
70	Combined	Conc	S8	35	15	258	Medium	35
71	Combined	Vct	S8	42	15	214	Medium	42
72	Combined	Vct	S8	42	15	216	High	42
73	Combined	Pvc	S8	12	15	21	Low	12
74	Combined	Conc	S15	44	15	162	Medium	44
75	Combined	Vct	S8	52	15	201	High	52
76	Combined	Pvc	S18	25	15	179	High	25
77	Combined	Vct	S8	35	15	259	Low	35
78	Combined	Pvc	S8	35	15	61	Low	35
79	Combined	Vct	S8	60	15	206	Medium	60
80	Combined	Conc	S21	46	15	112	High	46
81	Combined	Conc	S18	45	15	116	Medium	45
82	Combined	Ac	S8	46	15	188	Medium	46
83	Combined	Conc	S15	44	15	118	High	44
84	Combined	Conc	S21	46	15	113	Low	46

Corridor ID#	Sewer/Storm pipes	Sewer pipes types	Sewer Pipe diameter	Sewer pipe age	Sewer excavation depth	Corridor length	Sewer demand category	Sewer demand age
85	Combined	Conc	S18	46	15	107	Medium	46
86	Combined	Conc	S21	46	15	109	High	46
87	Combined	Ac	S8	36	15	13	High	36
88	Combined	Conc	S15	46	15	134	Low	46
89	Combined	Conc	S15	44	15	128	Low	44
90	Combined	Vct	S12	44	15	130	Medium	44
91	Combined	Vct	S10	45	15	215	High	45
92	Combined	Vct	S12	44	15	131	Medium	44
93	Combined	Conc	S15	44	15	129	Medium	44
94	Combined	Conc	S15	44	15	93	High	44
95	Combined	Conc	S15	44	15	94	Low	44
96	Combined	Conc	S15	44	15	90	Medium	44
97	Combined	Conc	S18	44	15	84	High	44
98	Combined	Conc	S18	44	15	88	High	44
99	Combined	Conc	S15	44	15	91	Low	44
100	Combined	Conc	S15	44	15	96	Low	44
101	Combined	Conc	S30	46	15	102	Medium	46
102	Combined	Conc	S12	46	15	138	High	46
103	Combined	Conc	S15	44	15	135	Medium	44
104	Combined	Conc	S8	44	15	194	Medium	44
105	Combined	Pvc	S8	7	15	40	High	7
106	Combined	Conc	S18	44	15	78	Low	44
107	Combined	Conc	S8	44	15	49	Medium	44
108	Combined	Vct	S12	44	15	75	High	44
109	Combined	Conc	S12	46	15	139	High	46
110	Combined	Vct	S12	44	15	149	Low	44
111	Combined	Pvc	S12	20	15	69	Low	20
112	Combined	Vct	S12	44	15	150	Medium	44
113	Combined	Pvc	S8	50	15	45	High	50
114	Combined	Pvc	S8	1	15	46	Medium	1
115	Combined	Ac	S8	46	15	189	Medium	46
116	Combined	Pvc	S12	20	15	70	High	20
117	Combined	Vct	S12	44	15	147	Low	44
118	Combined	Conc	S8	50	15	207	Medium	50
119	Combined	Ac	S8	46	15	190	High	46
120	Combined	Conc	S15	46	15	168	High	46
121	Combined	Vct	S10	44	15	154	Low	44
122	Combined	Conc	S15	46	15	169	Low	46
123	Combined	Conc	S8	44	15	159	Medium	44
124	Combined	Ac	S6	36	15	262	High	36
125	Combined	Conc	S8	44	15	199	Medium	44
126	Combined	Conc	S18	46	15	167	Medium	46

8.3.3 *Water network*

Table 8-26: *Town of Kindersley water network*

Corridor ID#	Water pipes	Water pipe types	Water Pipe diameter	Water pipe age	Water excavation depth	Corridor length	Water demand category	Water demand age
1	Wm	Pvc	S12	21	17	230	Medium	21
2	Wm	Pvc	S6	27	17	245	High	27
3	Wm	Pvc	S8	20	17	117	Medium	20
4	Wm	Pvc	S8	26	17	111	Medium	26
5	Wm	Pvc	S8	22	17	185	High	22
6	Wm	Pvc	S6	27	17	108	Low	27
7	Wm	Ac	S6	44	17	77	Medium	44
8	Wm	Uci	S6	50	17	120	High	50
9	Wm	Pvc	S6	27	17	20	High	27
10	Wm	Pvc	S6	27	17	253	Low	27
11	Wm	Ac	S6	37	17	32	Medium	37
12	Wm	Ac	S6	37	17	255	High	37
13	Wm	Pvc	S6	8	17	256	Medium	8
14	Wm	Pvc	S8	26	17	103	Medium	26
15	Wm	Pvc	S8	26	17	104	High	26
16	Wm	Pvc	S8	26	17	137	Low	26
17	Wm	Pvc	S8	9	17	140	Medium	9
18	Wm	Pvc	S6	9	17	115	High	9
19	Wm	Pvc	S6	9	17	143	High	9
20	Wm	Uci	S6	50	17	1	Low	50
21	Wm	Pvc	S8	22	17	186	Low	22
22	Wm	Pvc	S8	5	17	205	Medium	5
23	Wm	Pvc	S8	22	17	101	High	22
24	Wm	Ci	S6	58	17	133	Medium	58
25	Wm	Uci	S6	47	17	95	Medium	47
26	Wm	Ac	S6	44	17	89	High	44
27	Wm	Pvc	S8	22	17	110	Low	22
28	Wm	Ci	S8	57	17	83	Medium	57
29	Wm	Uci	S6	47	17	106	High	47
30	Wm	Pvc	S8	16	17	86	High	16
31	Wm	Ci	S6	57	17	81	Low	57
32	Wm	Pvc	S8	9	17	142	Low	9
33	Wm	Ci	S8	55	17	126	Medium	55
34	Wm	Ac	S6	36	17	76	High	36
35	Wm	Pvc	S6	27	17	37	Medium	27
36	Wm	Ci	S6	57	17	127	Medium	57
37	Wm	Uci	S6	50	17	121	High	50
38	Wm	Ci	S6	57	17	123	Low	57
39	Wm	Ci	S8	51	17	136	Medium	51
40	Wm	Ci	S8	51	17	124	High	51
41	Wm	Ci	S6	52	17	125	High	52

Corridor ID#	Water pipes	Water pipe types	Water Pipe diameter	Water pipe age	Water excavation depth	Corridor length	Water demand category	Water demand age
42	Wm	Ci	S8	51	17	148	Low	51
43	Wm	Pvc	S8	11	17	68	Low	11
44	Wm	Ac	S6	46	17	55	Medium	46
45	Wm	Ac	S6	42	17	34	High	42
46	Wm	Ci	S6	50	17	197	Medium	50
47	Wm	Ac	S6	45	17	153	Medium	45
48	Wm	Ac	S6	45	17	174	High	45
49	Wm	Ac	S6	45	17	210	Low	45
50	Wm	Ac	S6	44	17	158	Medium	44
51	Wm	Ac	S6	44	17	164	High	44
52	Wm	Ac	S6	50	17	228	High	50
53	Wm	Ac	S6	40	17	226	Low	40
54	Wm	Pvc	S6	29	17	64	Low	29
55	Wm	Pvc	S8	29	17	176	Medium	29
56	Wm	Pvc	S8	29	17	47	High	29
57	Wm	Pvc	S6	29	17	177	Medium	29
58	Wm	Ac	S8	34	17	5	Medium	34
59	Wm	Ac	S6	31	17	52	High	31
60	Wm	Pvc	S6	2	17	171	Low	2
61	Wm	Pvc	S16	25	17	265	Medium	25
62	Wm	Pvc	S12	21	17	232	High	21
63	Wm	Pvc	S6	26	17	222	High	26
64	Wm	Pvc	S6	50	17	221	Low	50
65	Wm	Pvc	S6	29	17	27	Low	29
66	Wm	Pvc	S6	27	17	33	Medium	27
67	Wm	Pvc	S6	27	17	243	High	27
68	Wm	Ac	S6	32	17	241	Medium	32
69	Wm	Pvc	S6	27	17	244	Medium	27
70	Wm	Pvc	S6	8	17	258	High	8
71	Wm	Ac	S6	32	17	214	Low	32
72	Wm	Plastic	S6	26	17	216	Medium	26
73	Wm	Pvc	S6	50	17	21	High	50
74	Wm	Ac	S6	42	17	162	High	42
75	Wm	Ac	S6	45	17	201	Low	45
76	Wm	Pvc	S8	25	17	179	Low	25
77	Wm	Pvc	S6	27	17	259	Medium	27
78	Wm	Ac	S6	35	17	61	High	35
79	Wm	Ac	S8	40	17	206	Medium	40
80	Wm	Pvc	S8	20	17	112	Medium	20
81	Wm	Pvc	S12	20	17	116	High	20
82	Wm	Ci	S8	51	17	188	Low	51
83	Wm	Pvc	S8	20	17	118	Medium	20
84	Wm	Ci	S6	60	17	113	High	60
85	Wm	Pvc	S8	22	17	107	High	22

Corridor ID#	Water pipes	Water pipe types	Water Pipe diameter	Water pipe age	Water excavation depth	Corridor length	Water demand category	Water demand age
86	Wm	Pvc	S8	27	17	109	Low	27
87	Wm	Pvc	S8	5	17	13	Low	5
88	Wm	Ci	S6	58	17	134	Medium	58
89	Wm	Ci	S8	55	17	128	High	55
90	Wm	Uci	S6	58	17	130	Medium	58
91	Wm	Ac	S6	42	17	215	Medium	42
92	Wm	Ci	S6	58	17	131	High	58
93	Wm	Uci	S6	50	17	129	Low	50
94	Wm	Ci	S8	55	17	93	Medium	55
95	Wm	Pvc	S6	50	17	94	High	50
96	Wm	Ci	S8	57	17	90	High	57
97	Wm	Ac	S6	44	17	84	Low	44
98	Wm	Pvc	S6	16	17	88	Low	16
99	Wm	Ci	S6	50	17	91	Medium	50
100	Wm	Uci	S6	47	17	96	High	47
101	Wm	Pvc	S8	16	17	102	Medium	16
102	Wm	Pvc	S8	11	17	138	Medium	11
103	Wm	Steel	S8	51	17	135	High	51
104	Wm	Ac	S6	44	17	194	Low	44
105	Wm	Ac	S6	36	17	40	Medium	36
106	Wm	Uci	S6	50	17	78	High	50
107	Wm	Uci	S6	50	17	49	High	50
108	Wm	Pvc	S6	50	17	75	Low	50
109	Wm	Pvc	S8	11	17	139	Low	11
110	Wm	Ci	S8	51	17	149	Medium	51
111	Wm	Uci	S6	60	17	69	High	60
112	Wm	Pvc	S6	9	17	150	Medium	9
113	Wm	Pvc	S6	9	17	45	Medium	9
114	Wm	Ci	S6	1	17	46	High	1
115	Wm	Ci	S8	51	17	189	Low	51
116	Wm	Pvc	S8	11	17	70	Medium	11
117	Wm	Ci	S6	50	17	147	High	50
118	Wm	Ac	S6	46	17	207	High	46
119	Wm	Pvc	S8	11	17	190	Low	11
120	Wm	Ac	S6	45	17	168	Low	45
121	Wm	Ac	S6	46	17	154	Medium	46
122	Wm	Ci	S6	54	17	169	High	54
123	Wm	Ac	S6	45	17	159	Medium	45
124	Wm	Ac	S6	42	17	262	Medium	42
125	Wm	Pvc	S16	26	17	199	High	26
126	Wm	Pvc	S8	28	17	167	Low	28

8.3.4 *Spatial analysis*

This section is devoted to discussing the spatial analysis of the town of Kindersley roads, water, and sewer networks.

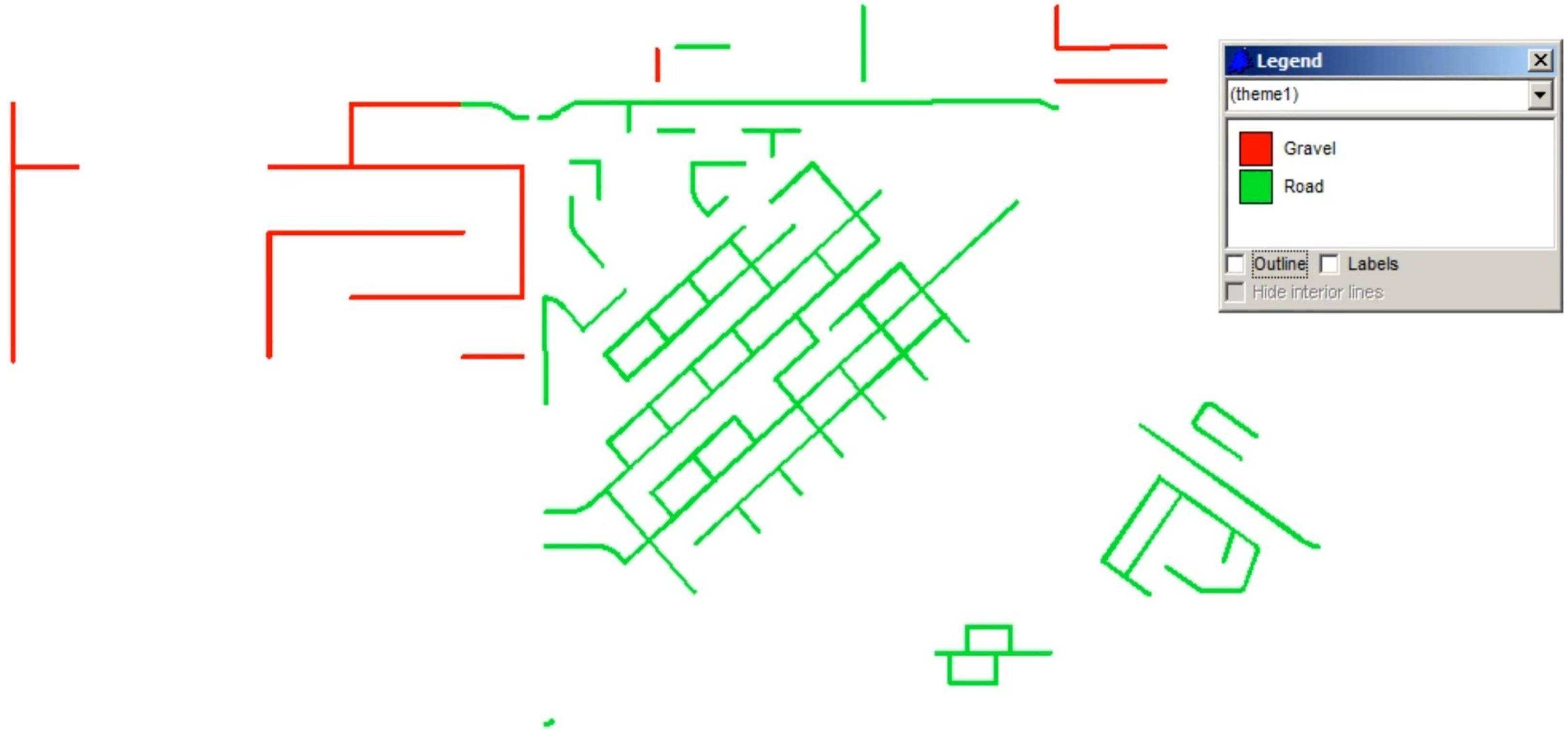


Figure 8.55: *Road types per surface paving material*

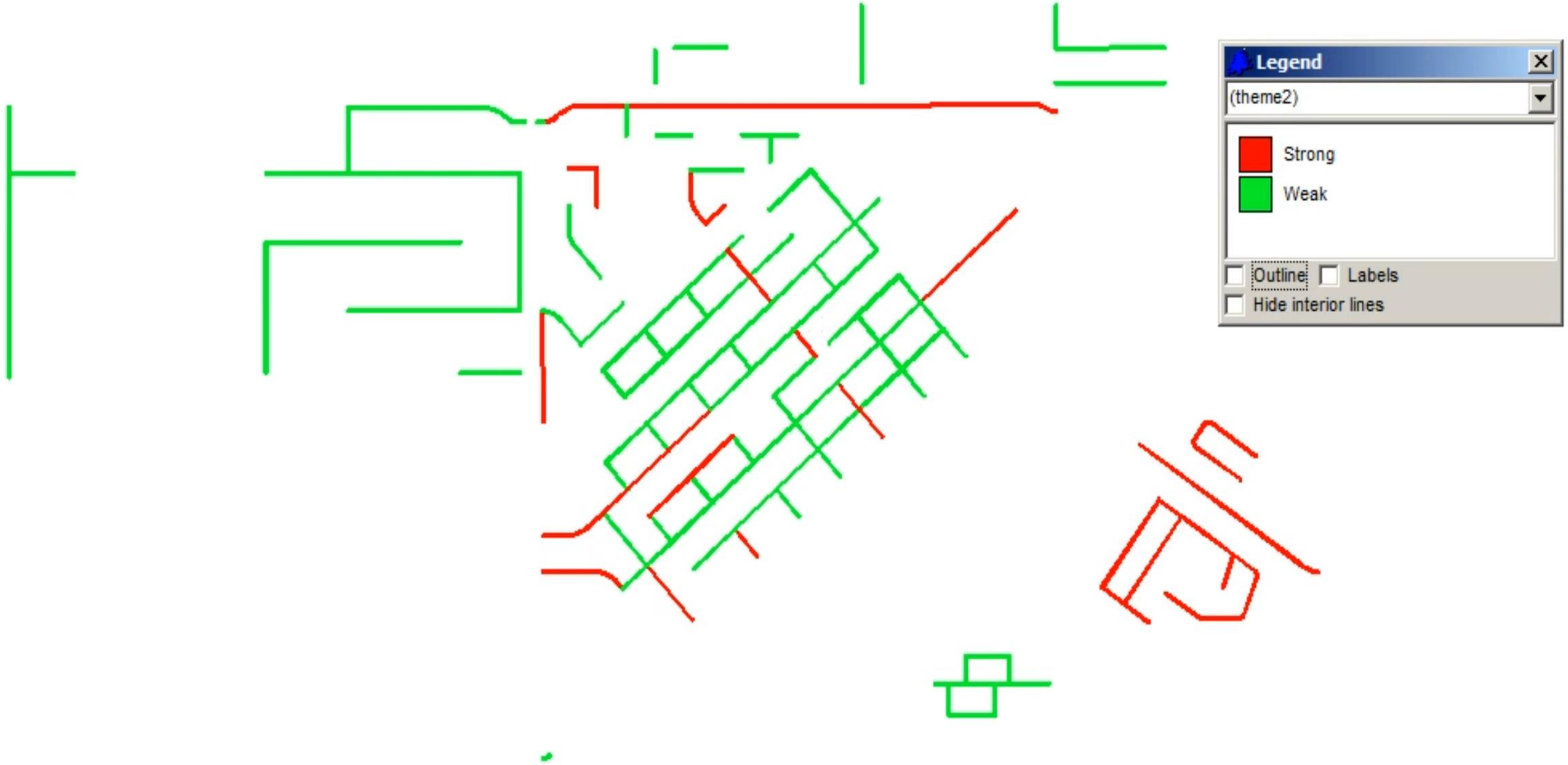


Figure 8.56: *Road structural categories*

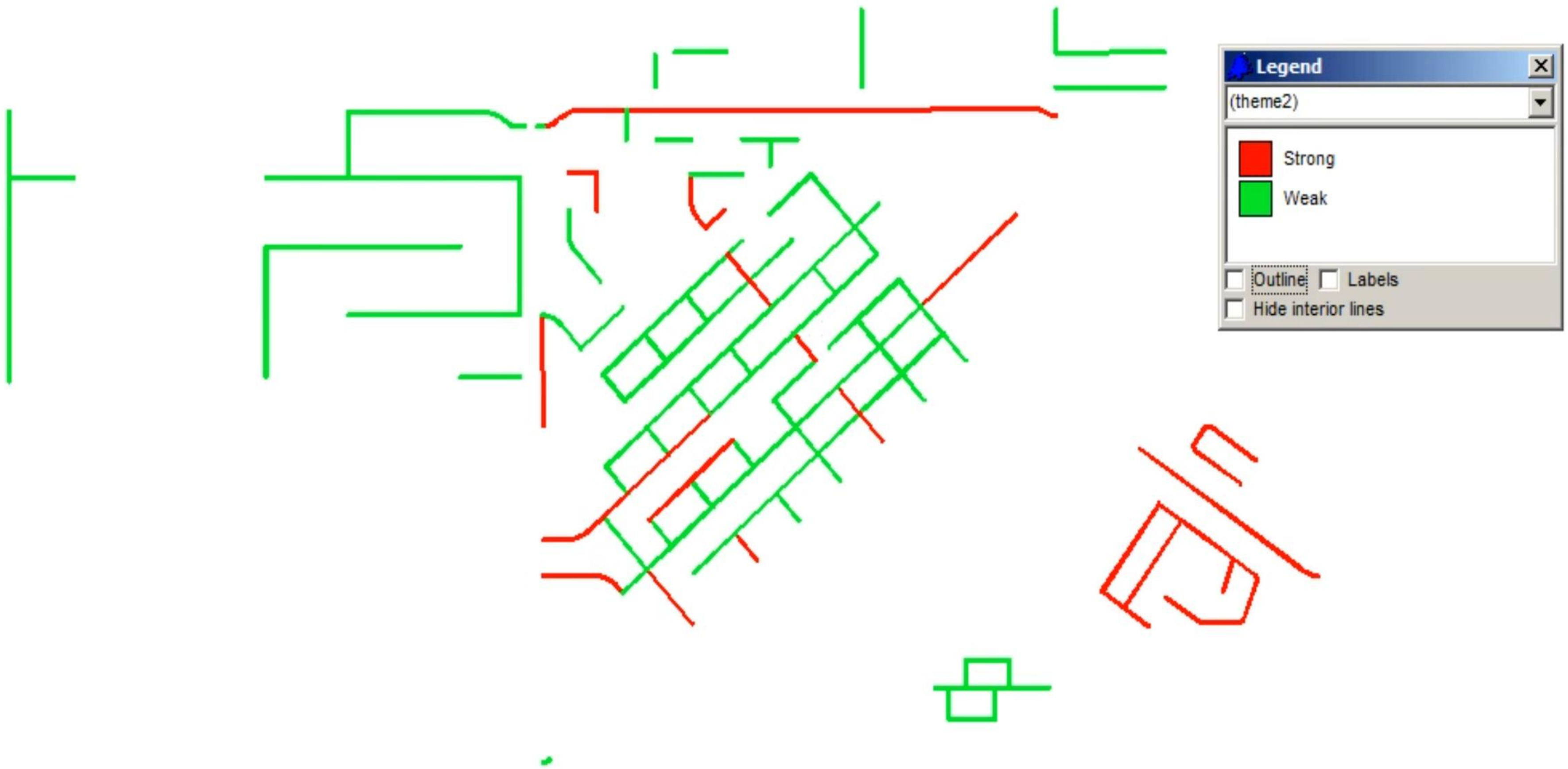


Figure 8.57: *Road structural categories*

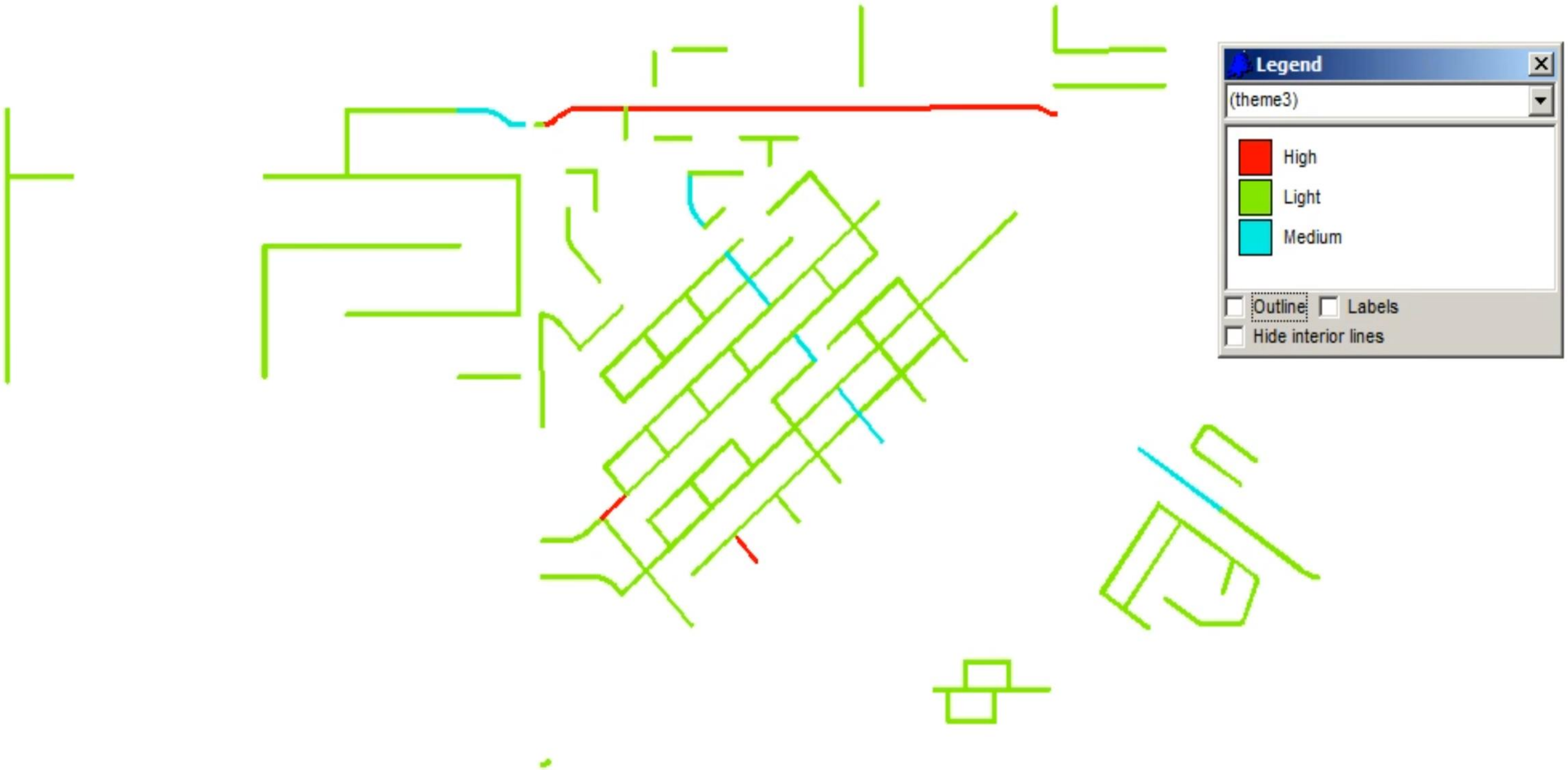


Figure 8.58: *Road traffic categories*

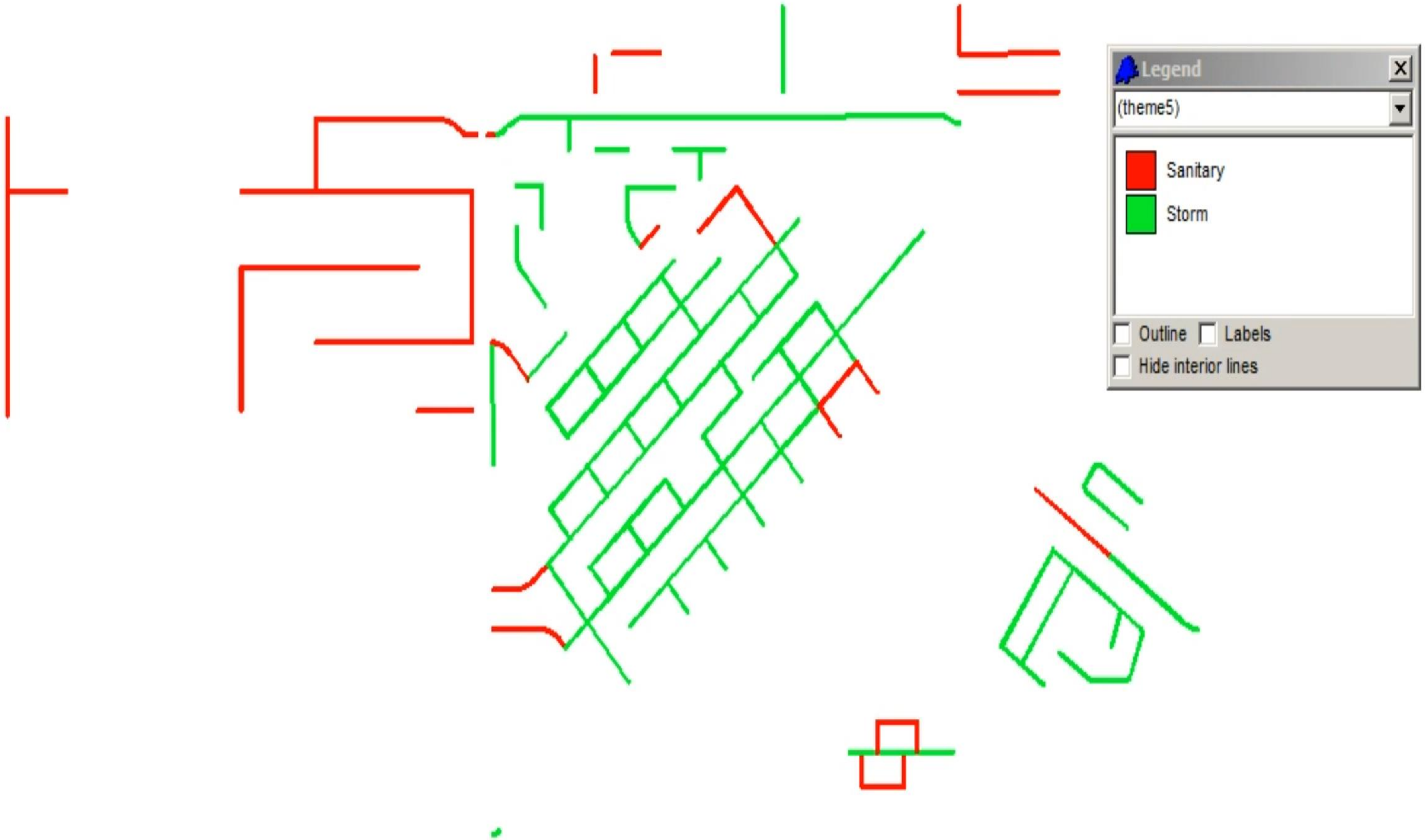


Figure 8.59: *Sewer pipes vs stormwater pipes*

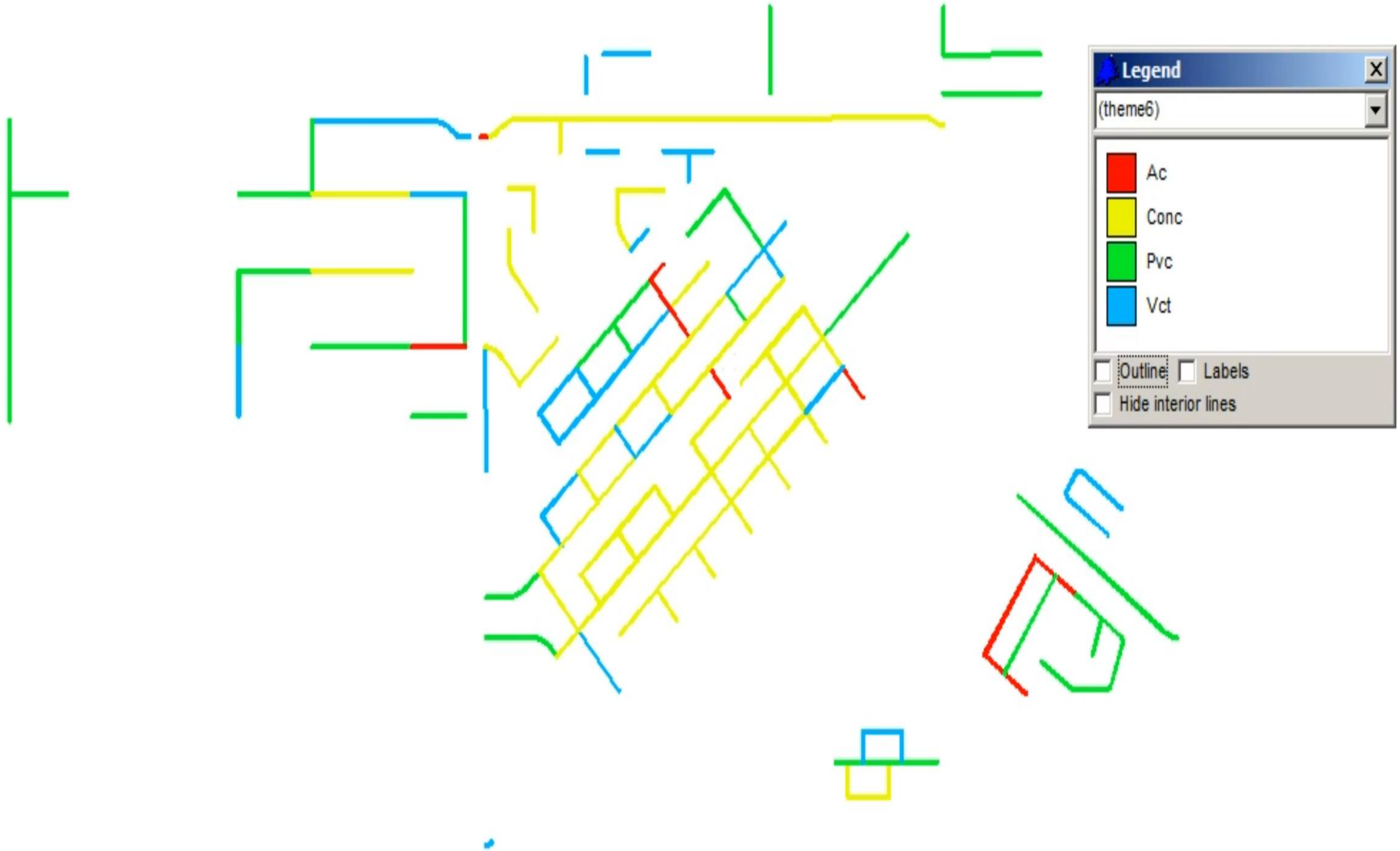


Figure 8.60: *Sewer pipes' materials*

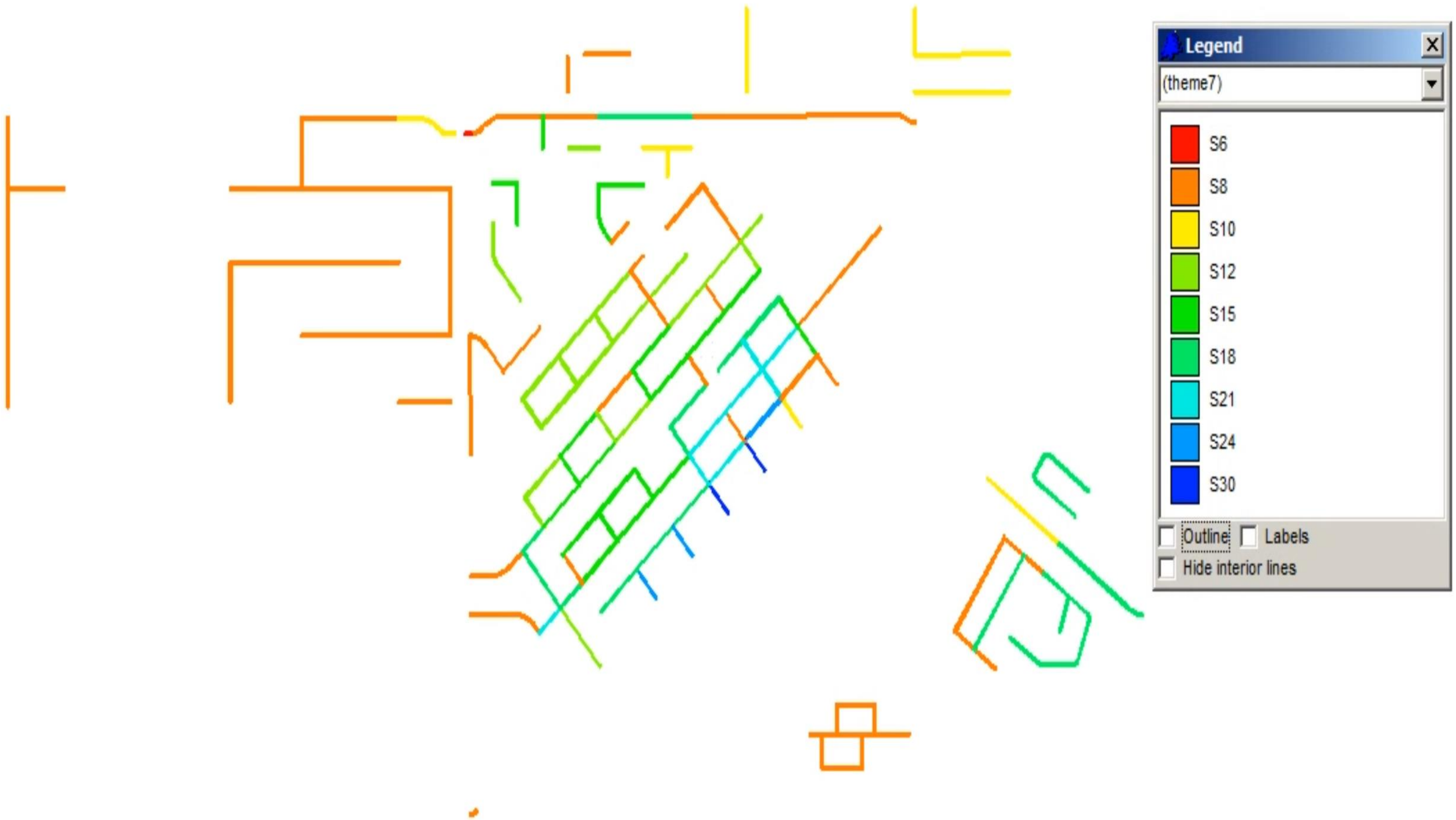


Figure 8.61: *Sewer pipes' diameters*

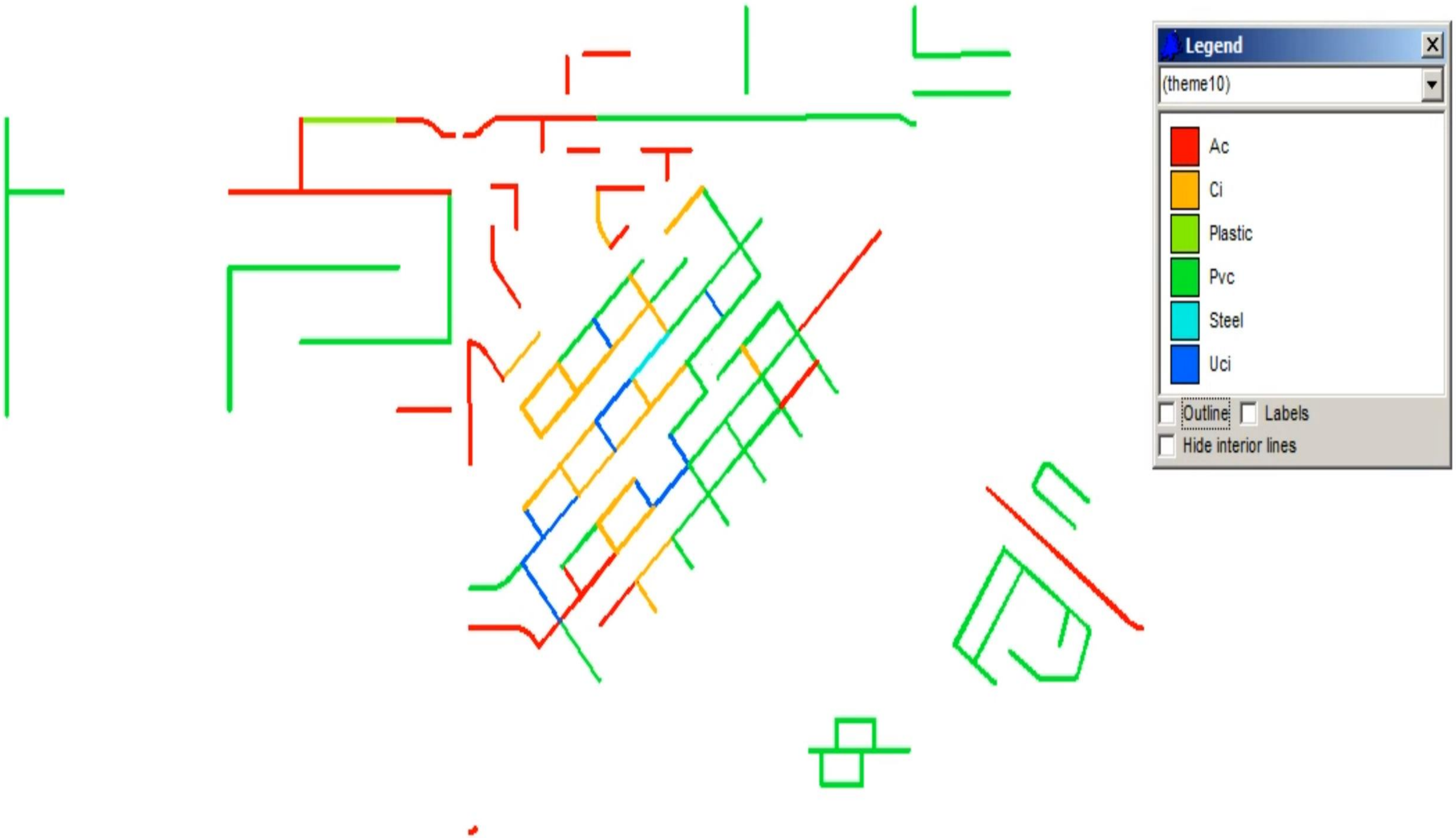


Figure 8.62: *Water pipes' materials*

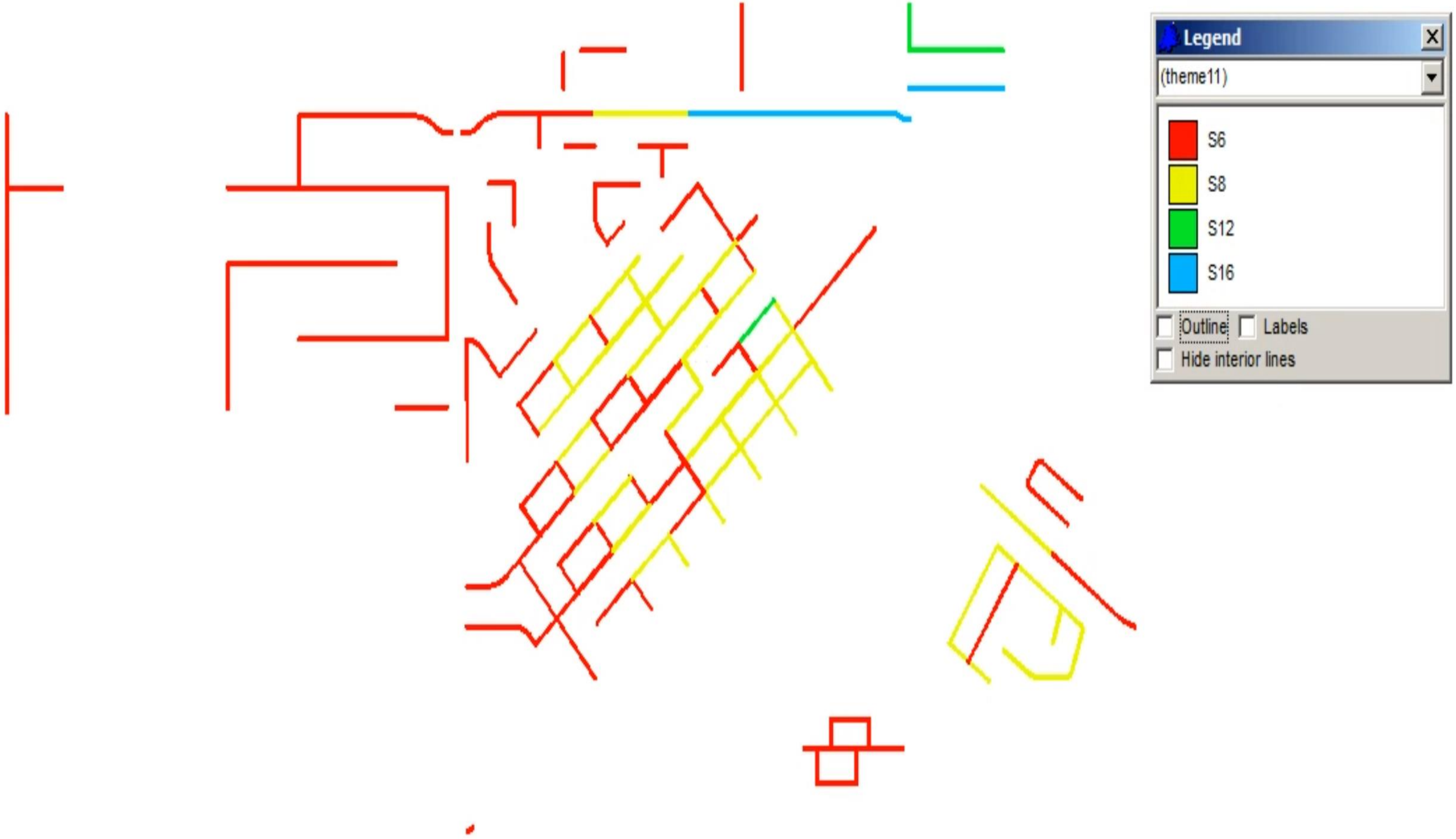


Figure 8.63: *Water pipes' diameters*

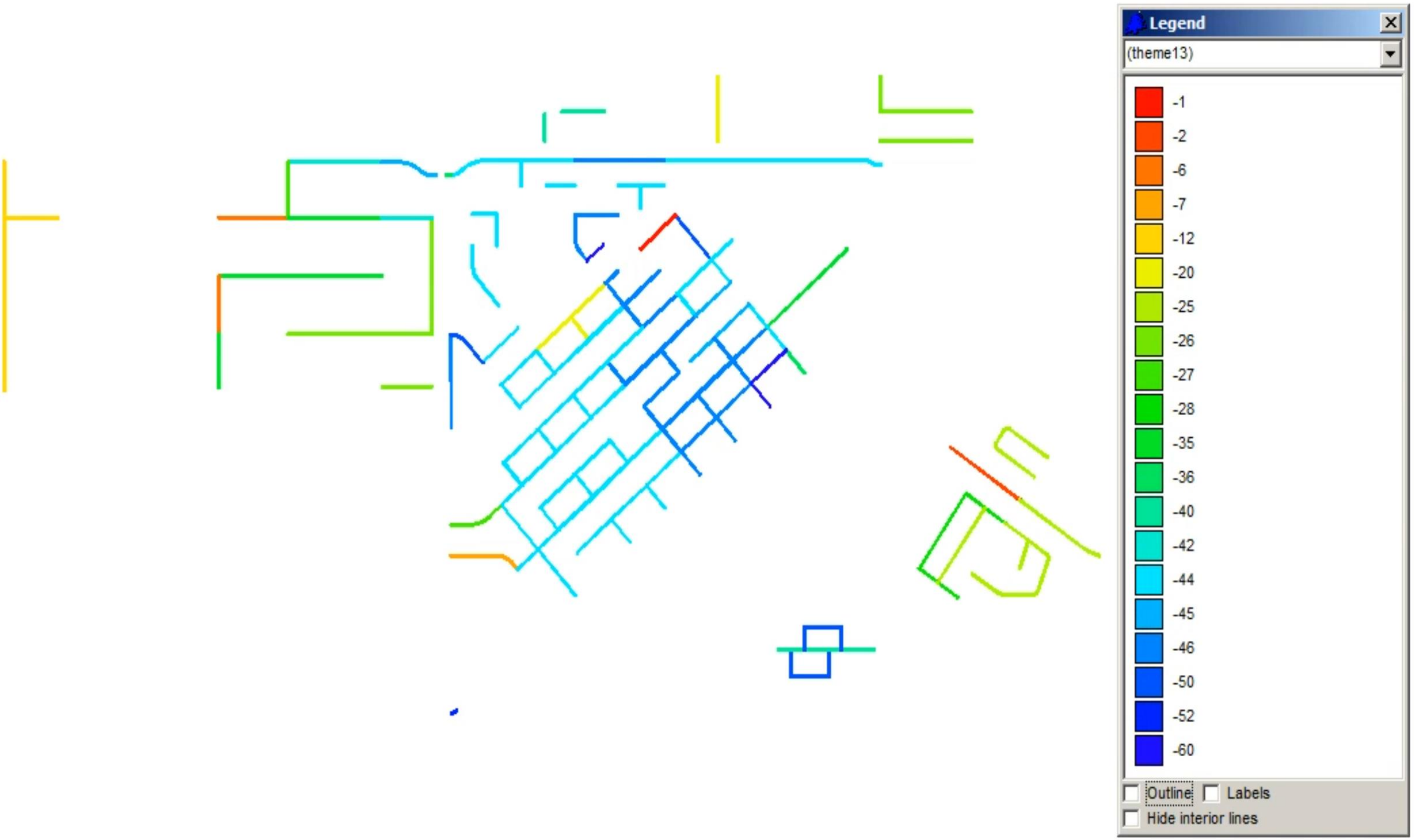


Figure 8.64: *Sewer pipes' ages (-ve age is used for programming purposes)*

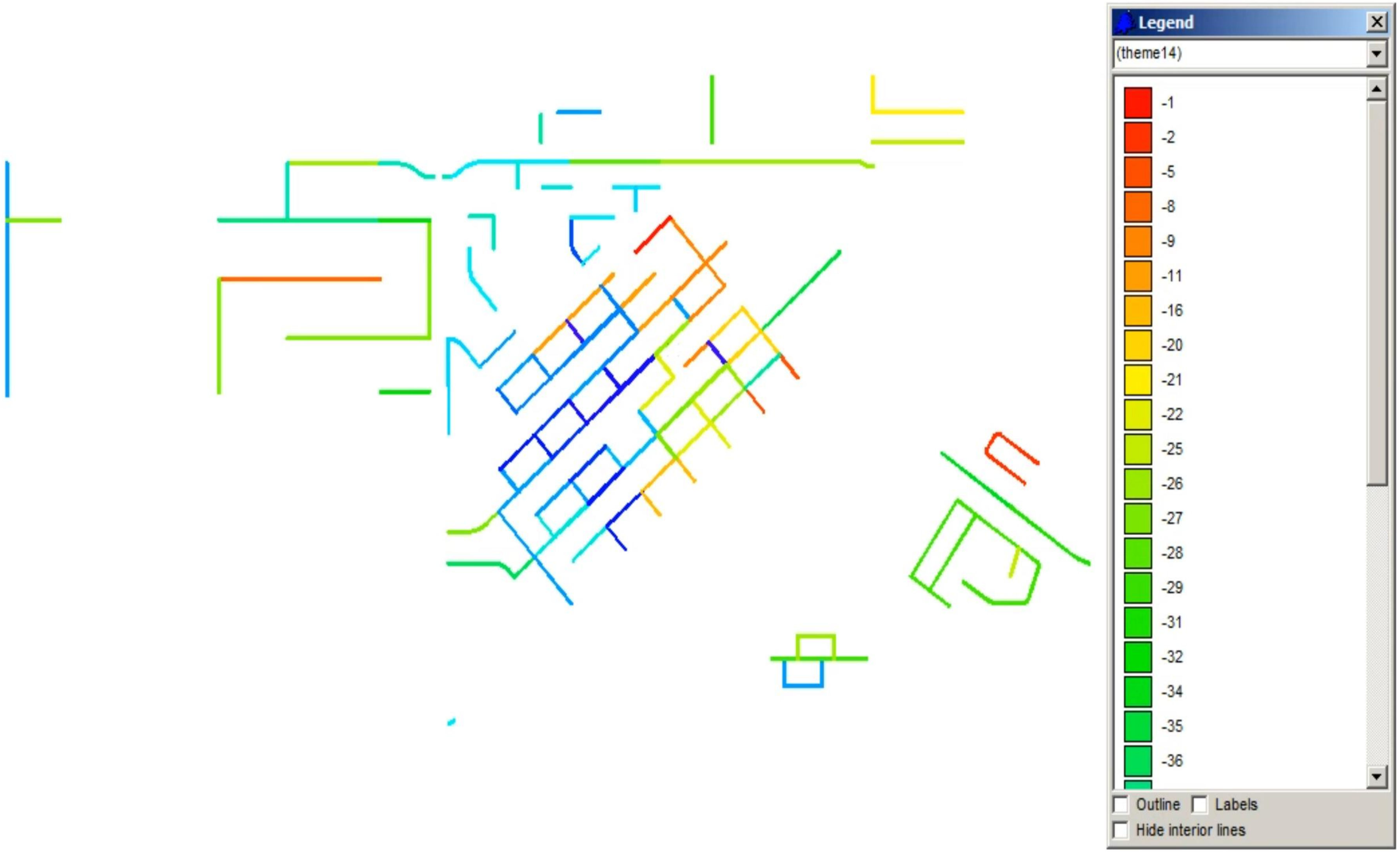


Figure 8.65: *Water pipes' ages (-ve age is used for programming purposes)*

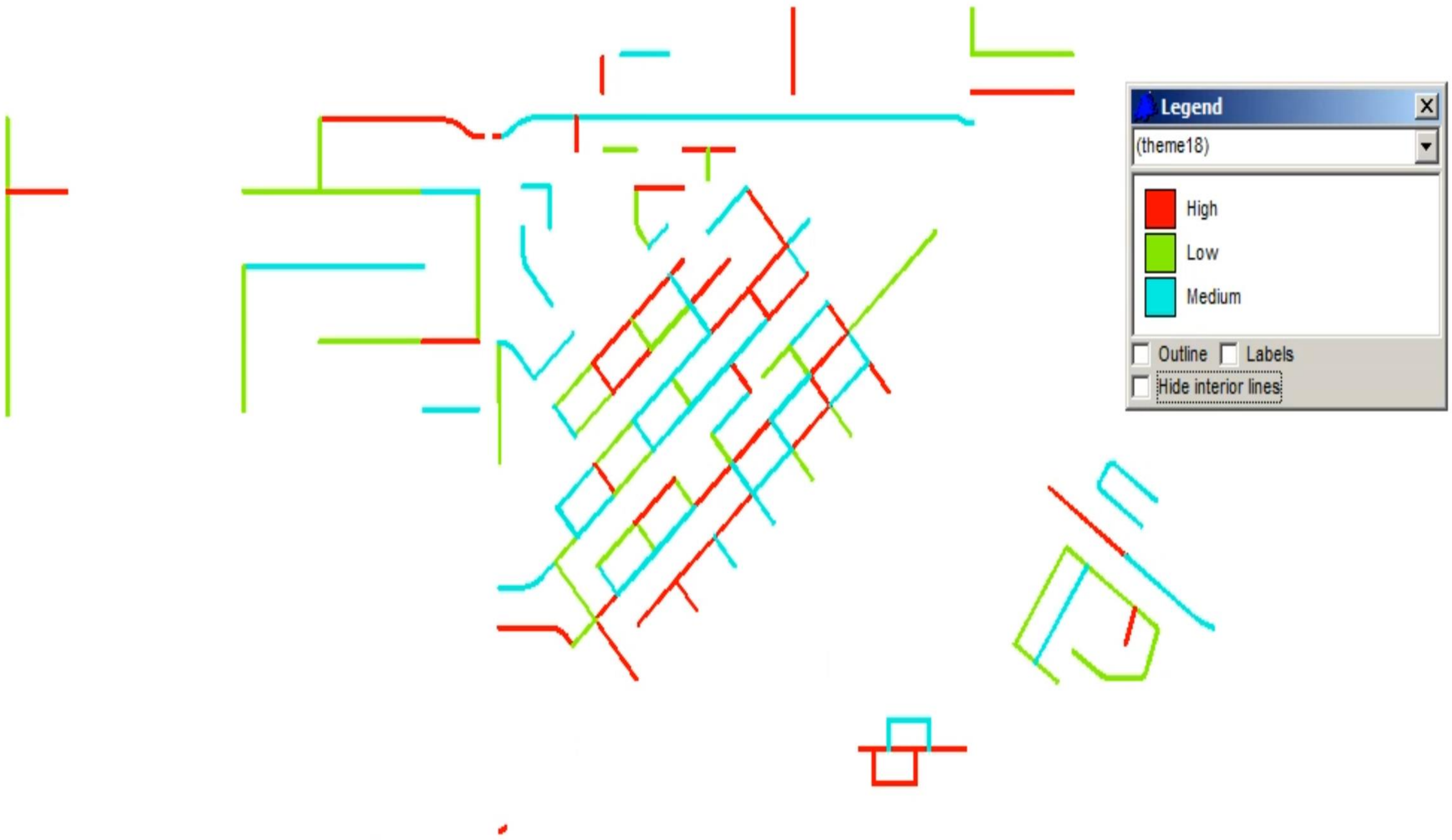


Figure 8.66: *Sewer pipes' demand categories*

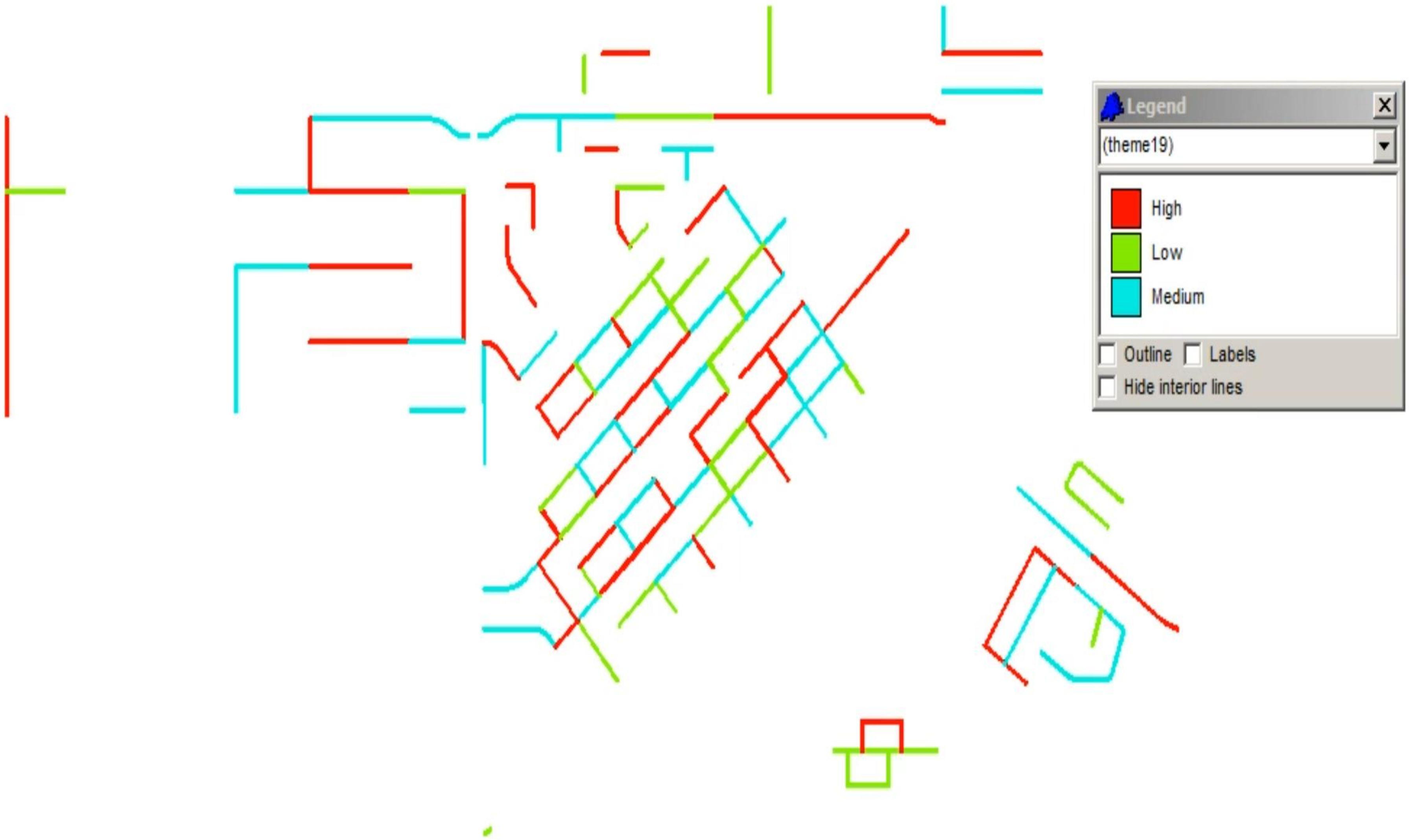


Figure 8.67: *Water pipes' demand categories*

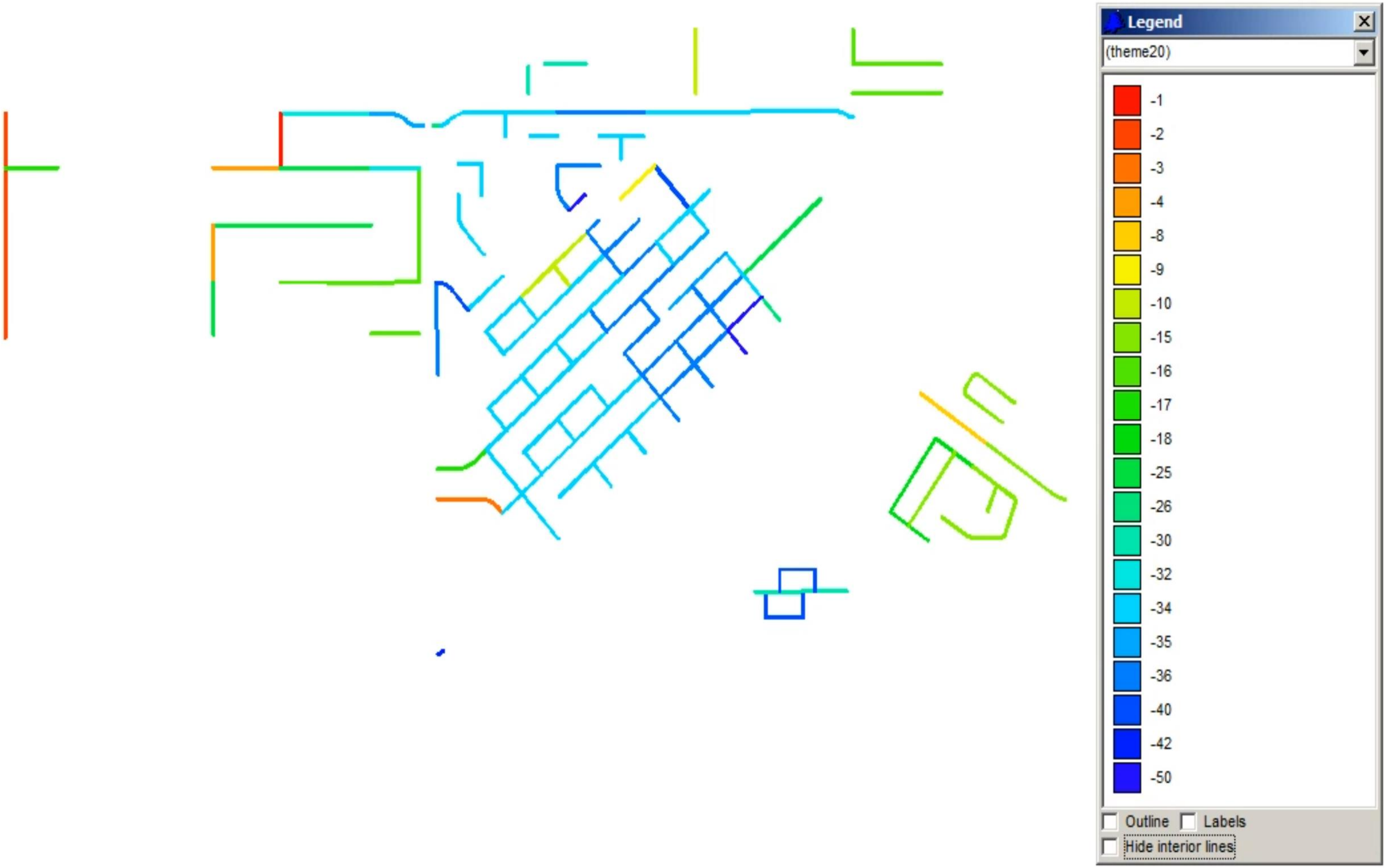


Figure 8.68: *Sewer pipes' demand age (-ve age is used for programming purposes)*

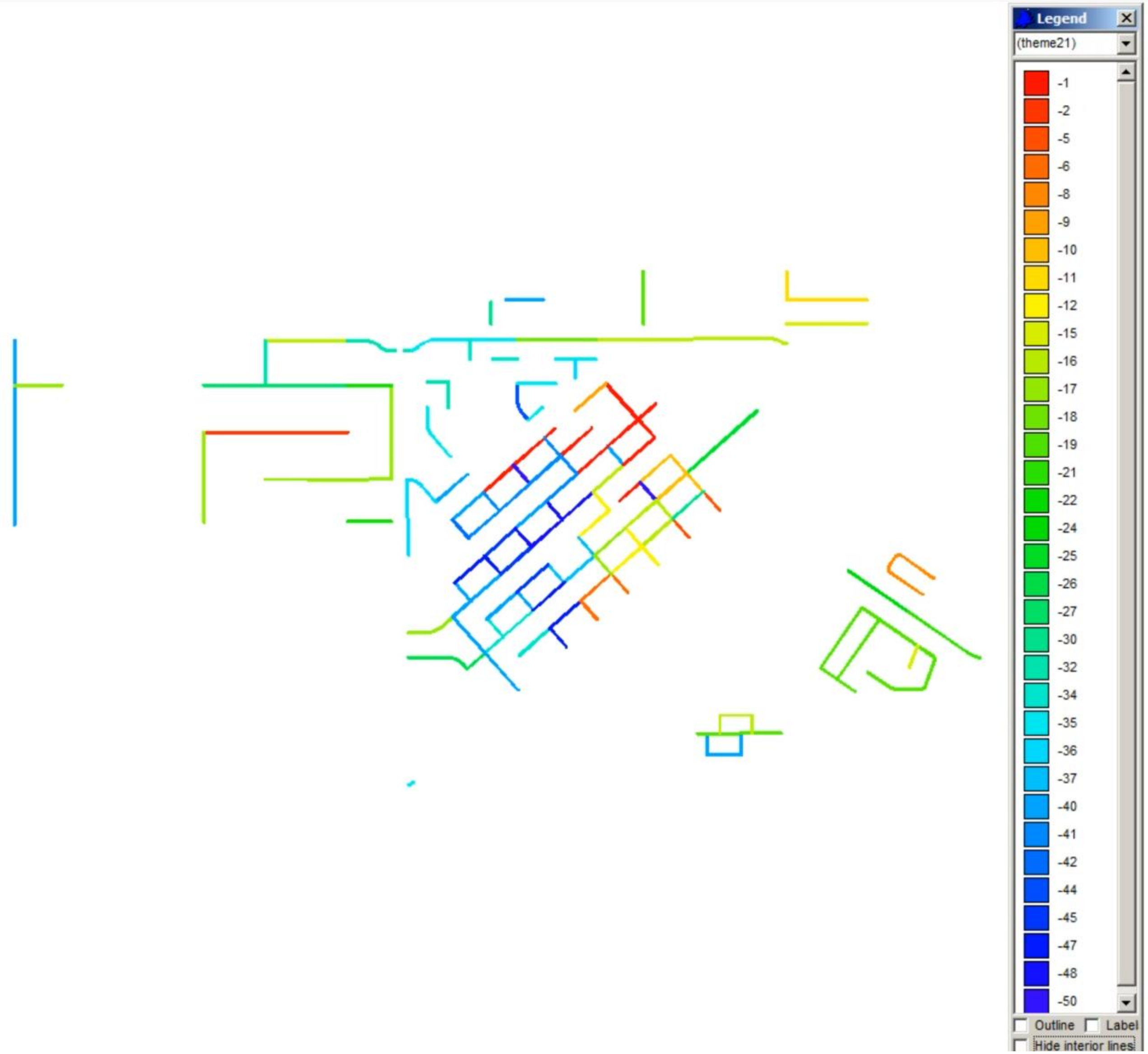


Figure 8.69: *Water pipes' demand age (-ve age is used for programming purposes)*

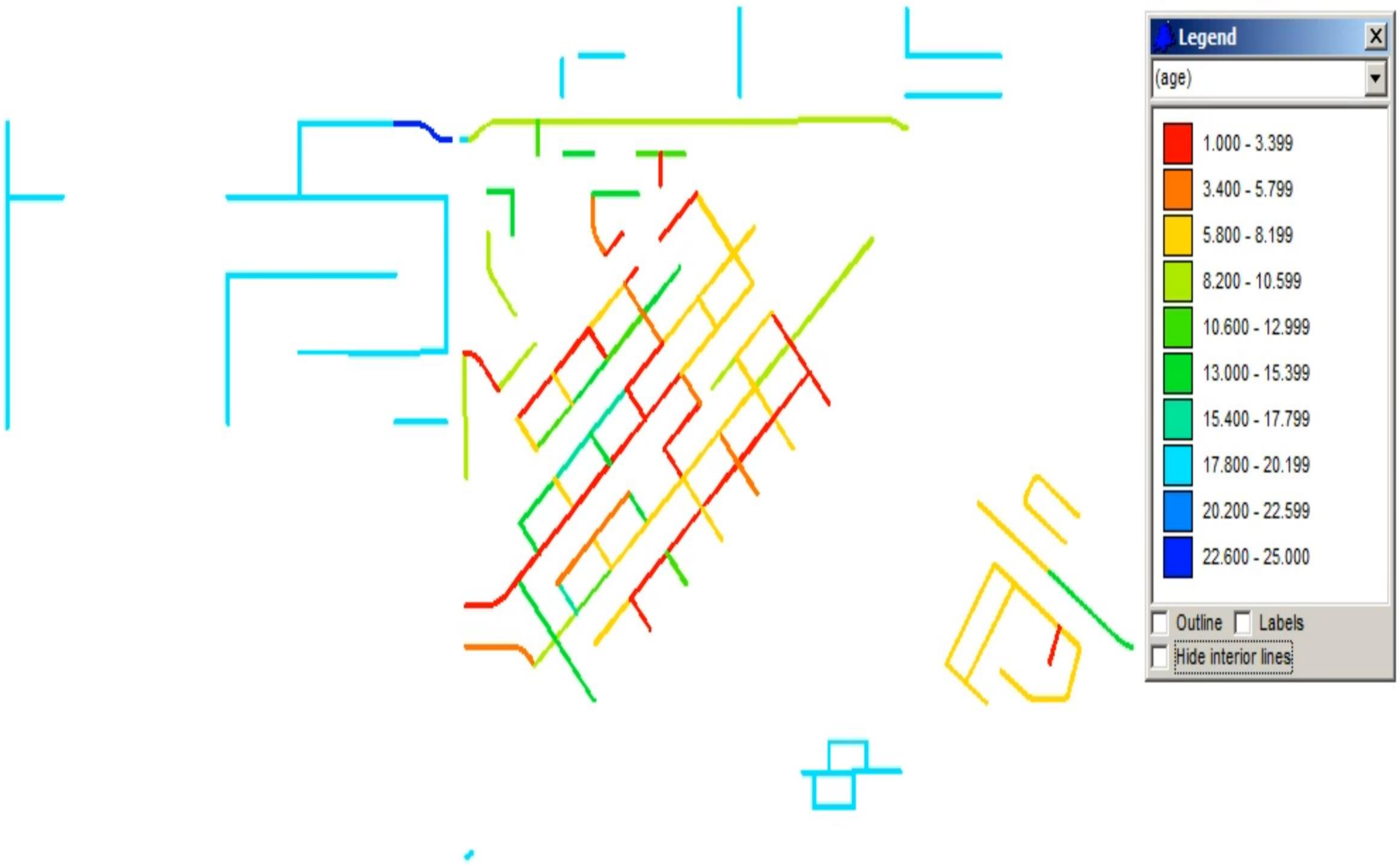


Figure 8.70: *Road age categories*

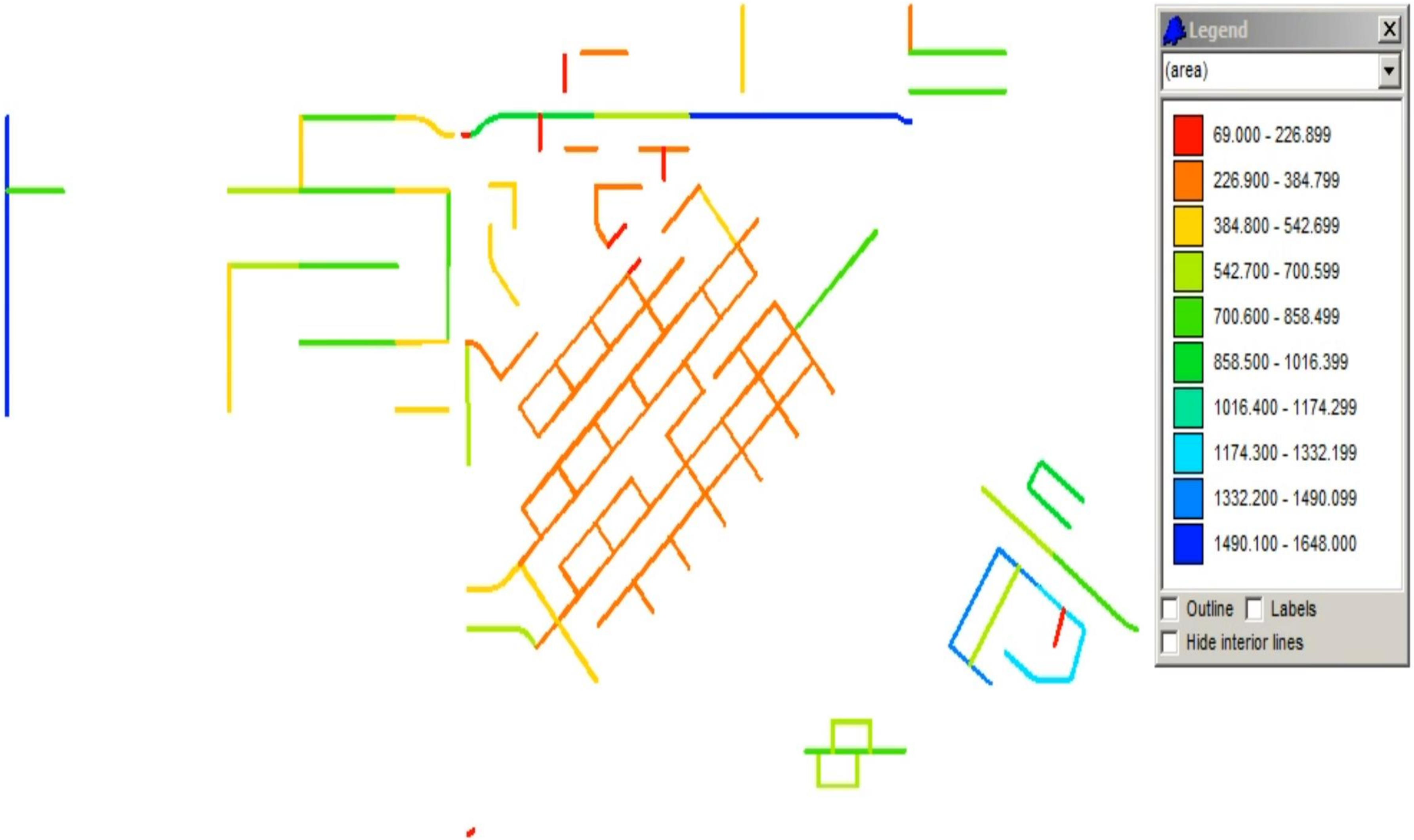
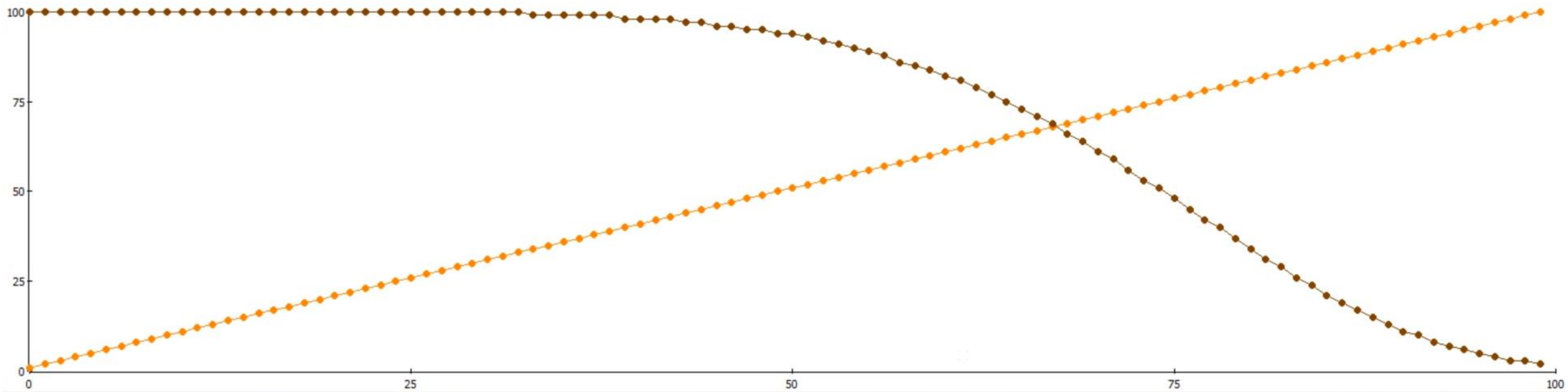


Figure 8.71: *Corridor length categories*

8.3.5 *Sample REMSOFT Yield Curves*

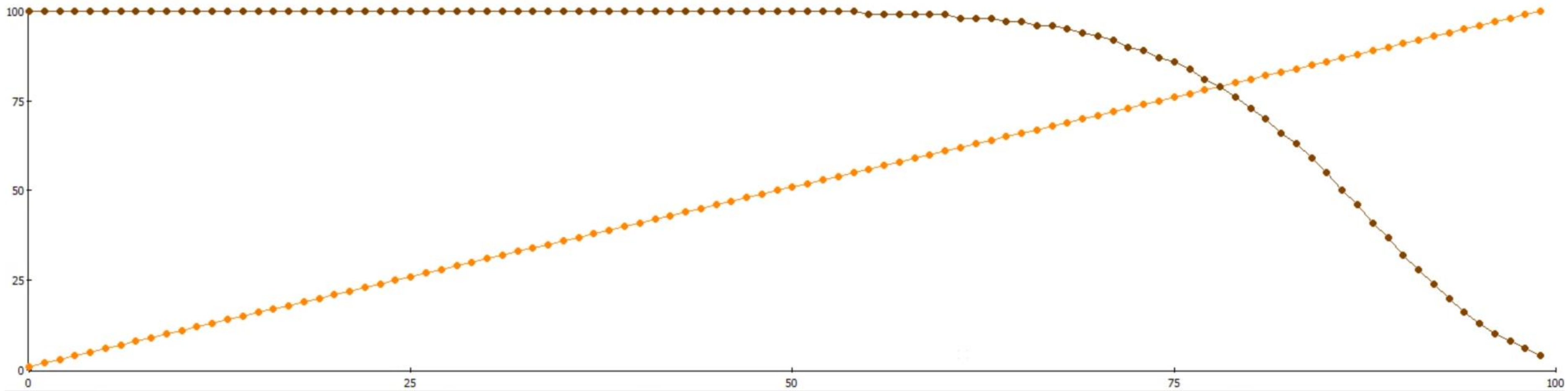
This section displays a sample of REMSOFT deterioration, demand-capacity ratio, repair cost, and repair time curve across the planning horizon. It is worth noting that those curves represent only a sample and not all the curves used in REMSOFT software. The difference between the curves varies according to the corridor/asset attributes (i.e. demand-capacity curve of a small diameter water plastic pipe with a low demand is different than a small diameter water plastic pipe with a high demand, small pipe diameters are different than medium or large pipe diameters, plastic pipes are different than concrete or iron pipes, water pipes are different than sewer pipes, etc.). Furthermore, the combinations are exponentially expanded in the partially-coordinated and fully-coordinated scenarios while dealing with pipes given the different possible combinations that could exist (i.e. pipe diameters, pipe materials, demand categories).



Show	Name		0	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18
YES	ytagesewer	●	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19
YES	ytreliabilitysewer	●	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100

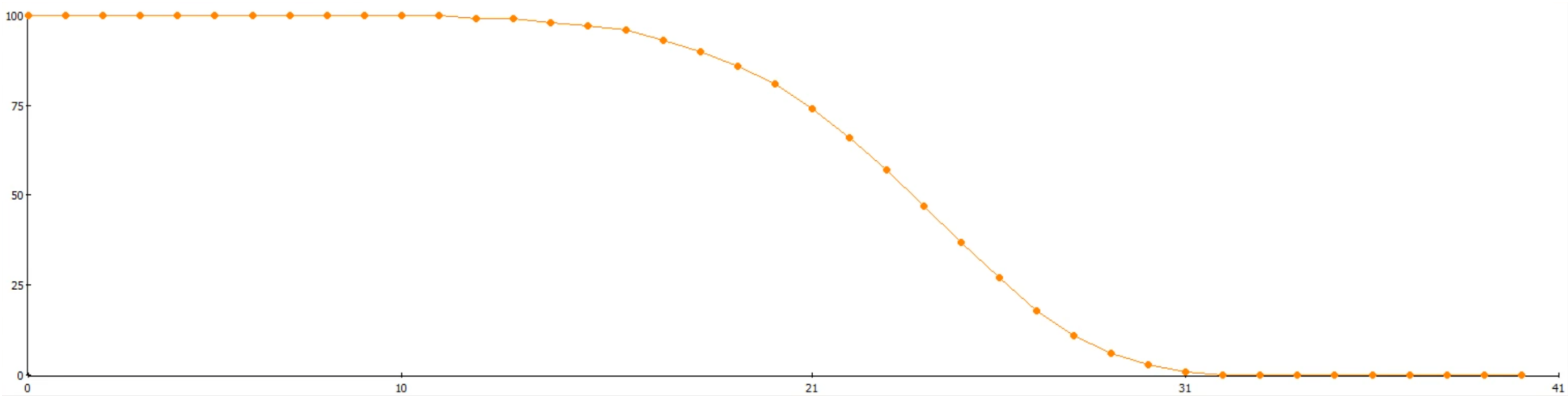
Show	Name		19	20	21	22	23	24	25	26	27	28	29	30	31	32	33	34	35	36
YES	ytagesewer	●	20	21	22	23	24	25	26	27	28	29	30	31	32	33	34	35	36	37
YES	ytreliabilitysewer	●	100	100	100	100	100	100	100	100	100	100	100	100	100	100	99	99	99	99

Figure 8.72: *Sample sewer deterioration curve*



Show	Name		0	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30	31	32	33	34	35	36	
YES	ytagewater	●	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30	31	32	33	34	35	36	37	
YES	ytreliabilitywater	●	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	1

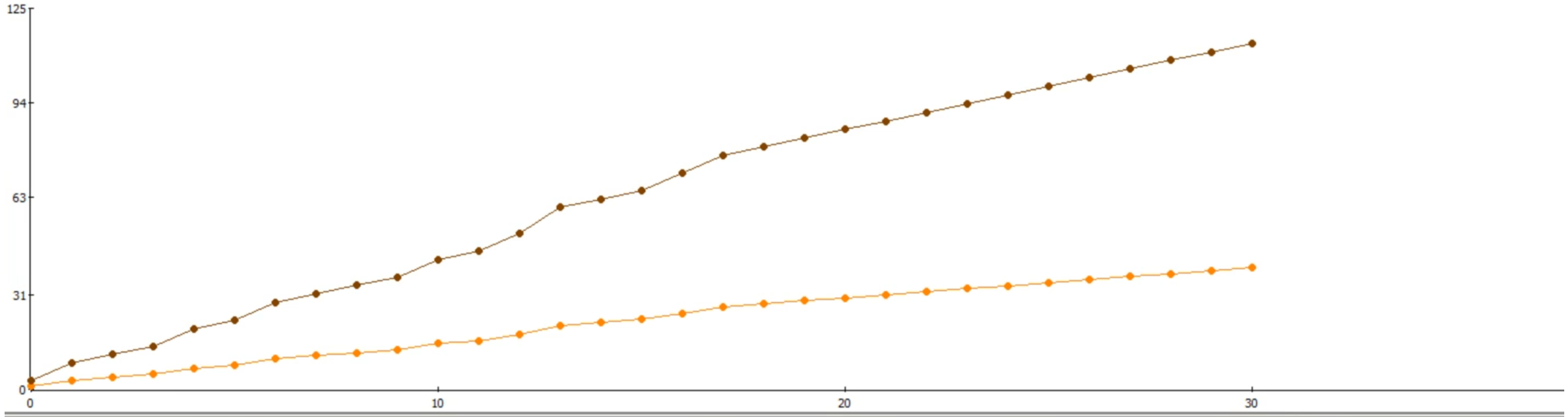
Figure 8.73: *Sample water deterioration curve*



Show	Name		0	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18
YES	ytPCIRoads	●	100	100	100	100	100	100	100	100	100	100	100	100	99	99	98	97	96	93	90

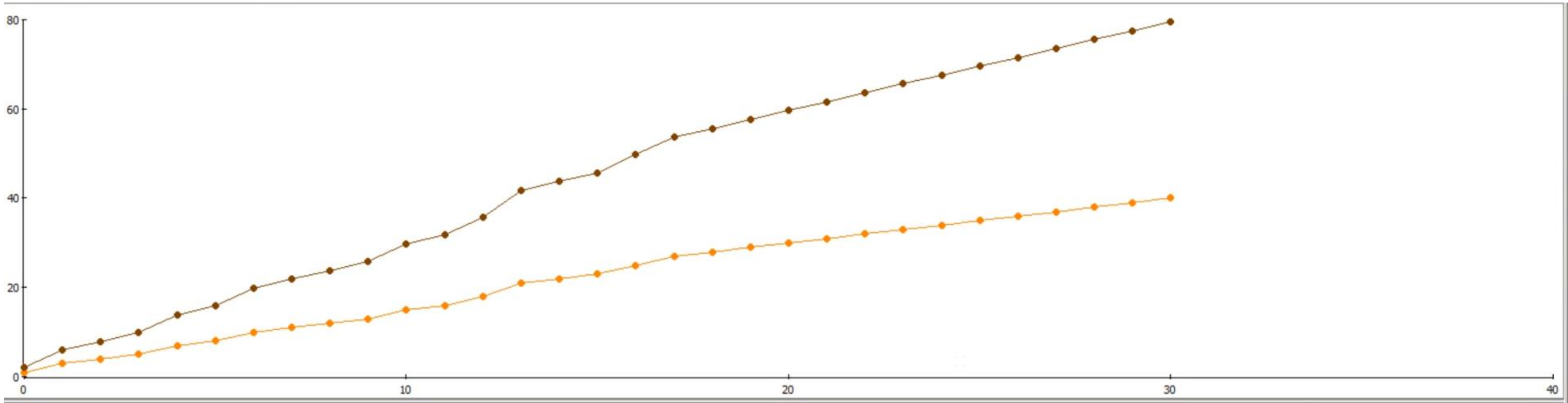
Show	Name	19	20	21	22	23	24	25	26	27	28	29	30	31	32	33	34	35	36	37
YES	ytPCIRoads	86	81	74	66	57	47	37	27	18	11	6	3	1	0	0	0	0	0	0

Figure 8.74: *Sample roads deterioration curve*



Show	Name		0	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30
YES	ytagesewercapacity	●	1	3	4	5	7	8	10	11	12	13	15	16	18	21	22	23	25	27	28	29	30	31	32	33	34	35	36	37	38	39	40
YES	Ytcapsewer	●	2.84	8.52	11.36	14.2	19.88	22.72	28.4	31.24	34.08	36.92	42.6	45.44	51.12	59.64	62.48	65.32	71	76.68	79.52	82.36	85.2	88.04	90.88	93.72	96.56	99.4	102.24	105.08	107.92	110.76	113.6

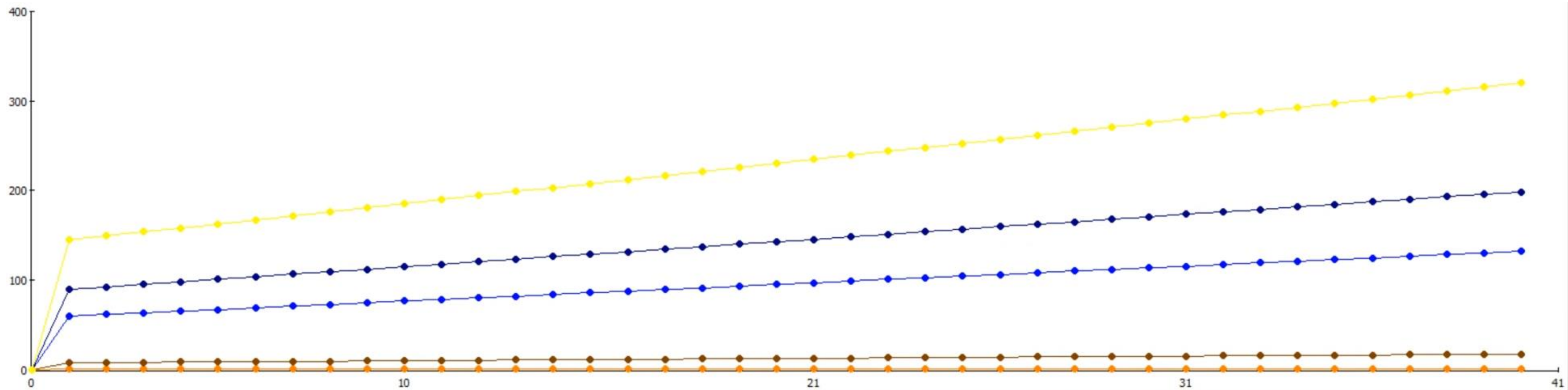
Figure 8.75: *Sample sewer demand-capacity curve*



Show	Name		0	1	2	3	4	5	6	7	8	9	10	11	12	13	14
YES	ytagewatercapacity	●	1	3	4	5	7	8	10	11	12	13	15	16	18	21	22
YES	Ytcapwater	●	1.988	5.964	7.952	9.94	13.916	15.904	19.88	21.868	23.856	25.844	29.82	31.808	35.784	41.748	43.736

Show	Name		15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	
YES	ytagewatercapacity	●	23	25	27	28	29	30	31	32	33	34	35	36	37	38	39	
YES	Ytcapwater	●	45.724	49.7	53.676	55.664	57.652	59.64	61.628	63.616	65.604	67.592	69.58	71.568	73.556	75.544	77.532	7

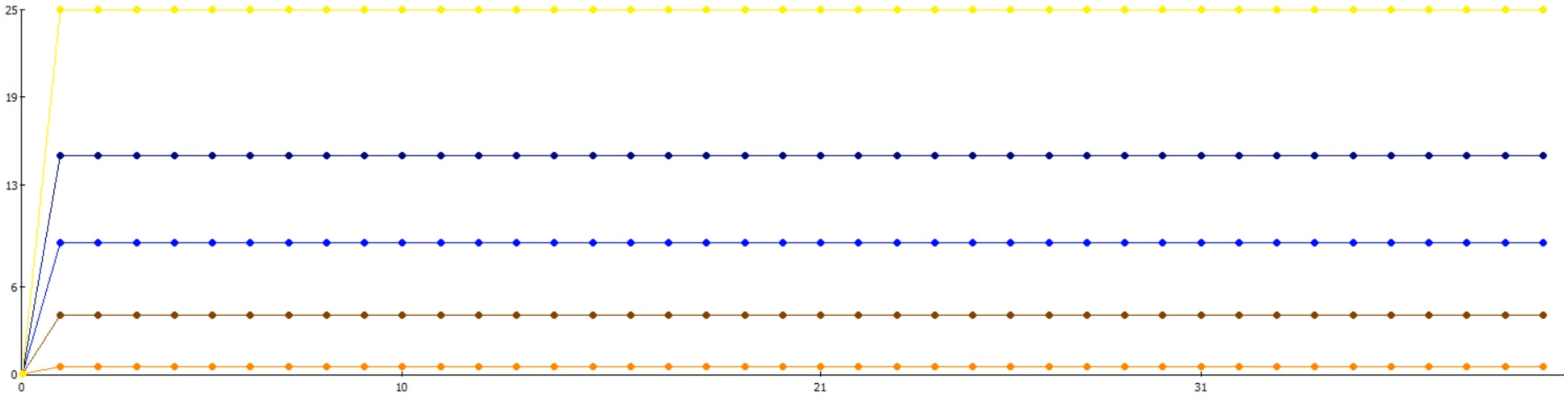
Figure 8.76: *Sample water demand-capacity curve*



Show	Name		0	1	2	3	4	5	6	7	8	9	10	11	12	13	14
YES	yCS$	●	0	0.75	0.77	0.8	0.82	0.84	0.87	0.89	0.91	0.94	0.96	0.98	1.01	1.03	1.05
YES	yMS$	●	0	8	8.25	8.5	8.74	8.99	9.24	9.49	9.73	9.98	10.23	10.48	10.72	10.97	11.22
YES	YRS$	●	0	60	61.86	63.72	65.58	67.43	69.29	71.15	73.01	74.87	76.73	78.58	80.44	82.3	84.16
YES	YPA$	●	0	90	92.79	95.58	98.36	101.15	103.94	106.73	109.51	112.3	115.09	117.88	120.66	123.45	126.24
YES	YRC$	●	0	145	149.49	153.98	158.47	162.97	167.46	171.95	176.44	180.93	185.42	189.92	194.41	198.9	203.39

Name	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30
yCS$	1.08	1.1	1.12	1.15	1.17	1.19	1.22	1.24	1.26	1.29	1.31	1.33	1.36	1.38	1.4	1.43
yMS$	11.47	11.72	11.96	12.21	12.46	12.71	12.95	13.2	13.45	13.7	13.94	14.19	14.44	14.69	14.94	15.18
YRS$	86.02	87.88	89.74	91.59	93.45	95.31	97.17	99.03	100.89	102.74	104.6	106.46	108.32	110.18	112.04	113.9
YPA$	129.03	131.82	134.6	137.39	140.18	142.97	145.75	148.54	151.33	154.12	156.9	159.69	162.48	165.27	168.06	170.84
YRC$	207.88	212.37	216.86	221.36	225.85	230.34	234.83	239.32	243.81	248.31	252.8	257.29	261.78	266.27	270.76	275.25

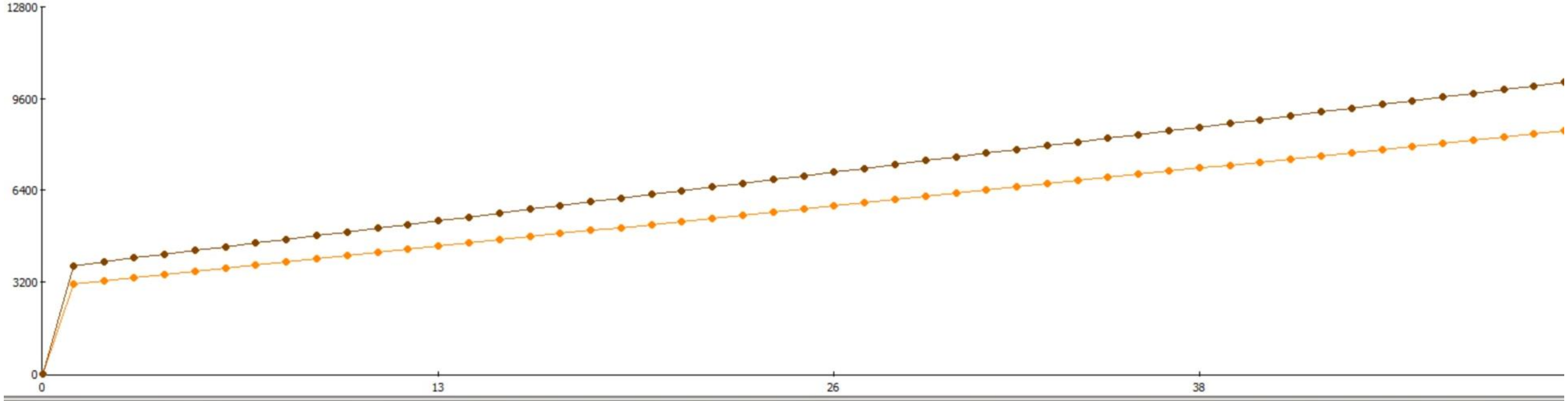
Figure 8.77: *Sample roads repair cost curve*



Show	Name		0	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18
YES	yCSL		0	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5
YES	yMSL		0	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4
YES	YRSL		0	9	9	9	9	9	9	9	9	9	9	9	9	9	9	9	9	9	9
YES	YPAL		0	15	15	15	15	15	15	15	15	15	15	15	15	15	15	15	15	15	15
YES	YRCL		0	25	25	25	25	25	25	25	25	25	25	25	25	25	25	25	25	25	25

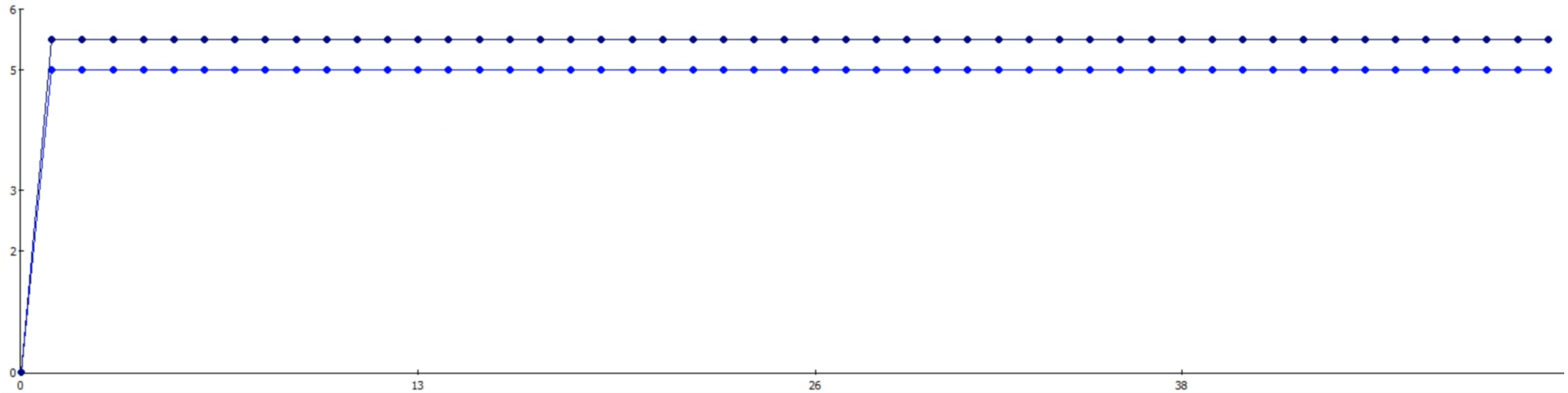
Name	19	20	21	22	23	24	25	26	27	28	29	30	31	32	33	34	35	36	37
yCSL	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5
yMSL	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4
YRSL	9	9	9	9	9	9	9	9	9	9	9	9	9	9	9	9	9	9	9
YPAL	15	15	15	15	15	15	15	15	15	15	15	15	15	15	15	15	15	15	15
YRCL	25	25	25	25	25	25	25	25	25	25	25	25	25	25	25	25	25	25	25

Figure 8.78: *Sample roads repair time curve*



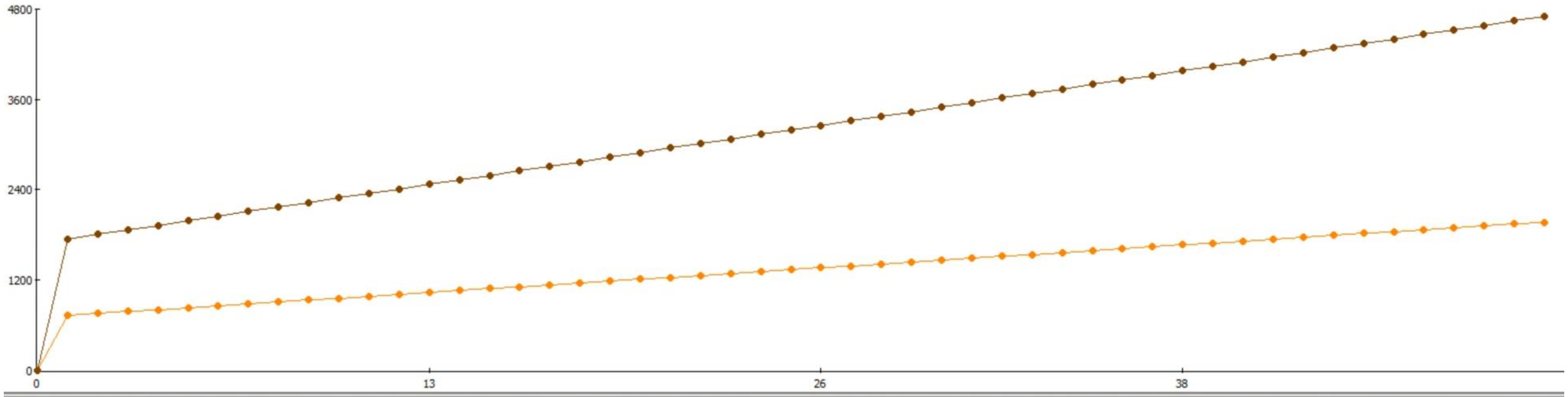
Show	Name		0	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25
YES	yRDSR-HD1$		0	3151	3259.76	3368.51	3477.27	3586.02	3694.78	3803.53	3912.29	4021.04	4129.8	4238.55	4347.31	4456.06	4564.82	4673.57	4782.33	4891.08	4999.84	5108.59	5217.35	5326.1	5434.86	5543.61	5652.37	5761.12
YES	yRDSR-HD2$		0	3780	3910.49	4040.98	4171.47	4301.96	4432.45	4562.94	4693.43	4823.92	4954.41	5084.9	5215.39	5345.88	5476.37	5606.86	5737.35	5867.84	5998.33	6128.82	6259.31	6389.8	6520.29	6650.78	6781.27	6911.76

Figure 8.79: *Sample sewer repair cost curve*



Show	Name		0	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30	31	32	33	34	35	36
YES	yRDSR-LD1L		0	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5
YES	yRDSR-LD2L		0	5.5	5.5	5.5	5.5	5.5	5.5	5.5	5.5	5.5	5.5	5.5	5.5	5.5	5.5	5.5	5.5	5.5	5.5	5.5	5.5	5.5	5.5	5.5	5.5	5.5	5.5	5.5	5.5	5.5	5.5	5.5	5.5	5.5	5.5	5.5	5.5
YES	yRDSR-HD1L		0	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5
YES	yRDSR-HD2L		0	5.5	5.5	5.5	5.5	5.5	5.5	5.5	5.5	5.5	5.5	5.5	5.5	5.5	5.5	5.5	5.5	5.5	5.5	5.5	5.5	5.5	5.5	5.5	5.5	5.5	5.5	5.5	5.5	5.5	5.5	5.5	5.5	5.5	5.5	5.5	5.5

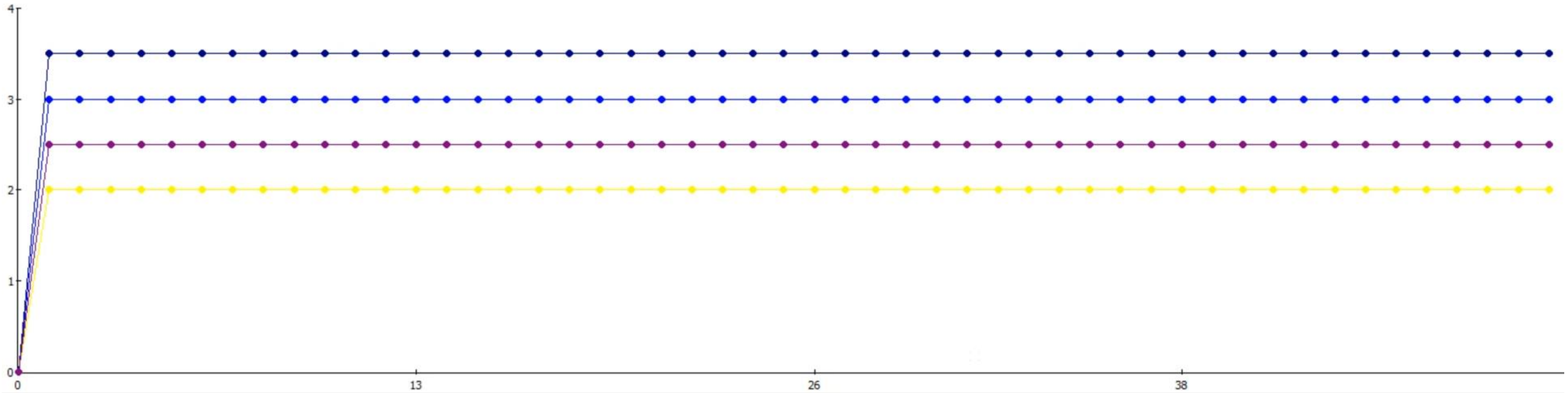
Figure 8.80: *Sample sewer repair time curve*



Show	Name		0	1	2	3	4	5	6	7	8	9	10	11	12
YES	ylinerwater-LD1$	●	0	732.2	757.48	782.76	808.04	833.33	858.61	883.89	909.17	934.45	959.73	985.02	1010.3
YES	ylinerwater-LD2$	●	0	1747.6	1807.93	1868.26	1928.59	1988.91	2049.24	2109.57	2169.9	2230.23	2290.56	2350.89	2411.21

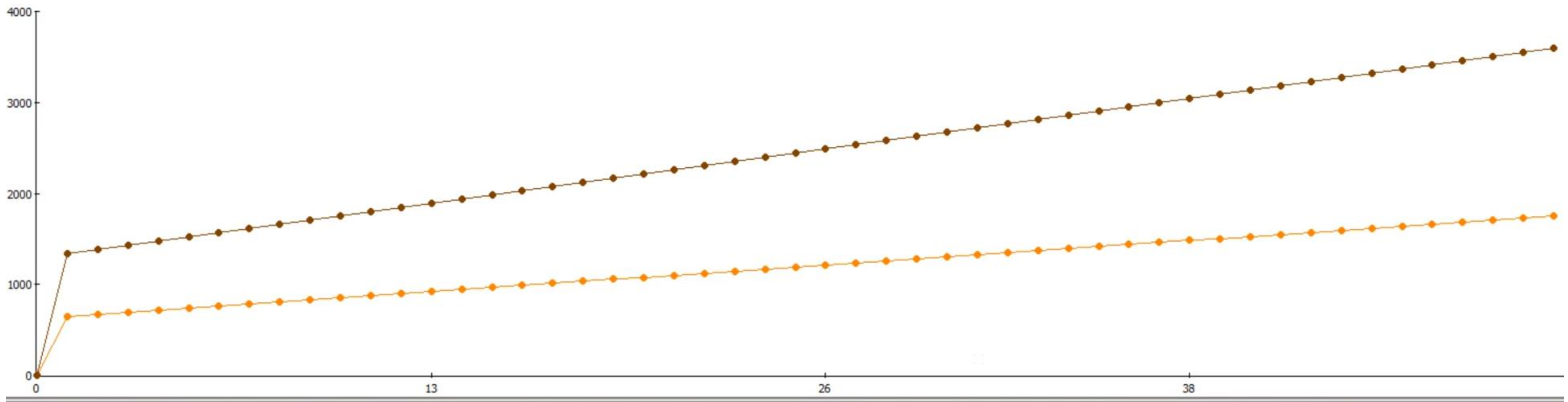
Name	13	14	15	16	17	18	19	20	21	22	23	24	25
ylinerwater-LD1$	1035.58	1060.86	1086.14	1111.42	1136.71	1161.99	1187.27	1212.55	1237.83	1263.11	1288.4	1313.68	1338.96
ylinerwater-LD2$	2471.54	2531.87	2592.2	2652.53	2712.86	2773.19	2833.51	2893.84	2954.17	3014.5	3074.83	3135.16	3195.49

Figure 8.81: *Sample water repair cost curve*



Show	Name		0	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30	31	32	33	34	35
YES	yreplacewater-LD1L	●	0	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3
YES	yreplacewater-LD2L	●	0	3.5	3.5	3.5	3.5	3.5	3.5	3.5	3.5	3.5	3.5	3.5	3.5	3.5	3.5	3.5	3.5	3.5	3.5	3.5	3.5	3.5	3.5	3.5	3.5	3.5	3.5	3.5	3.5	3.5	3.5	3.5	3.5	3.5	3.5	3.5
YES	yreplacewater-HD1L	●	0	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3
YES	yreplacewater-HD2L	●	0	3.5	3.5	3.5	3.5	3.5	3.5	3.5	3.5	3.5	3.5	3.5	3.5	3.5	3.5	3.5	3.5	3.5	3.5	3.5	3.5	3.5	3.5	3.5	3.5	3.5	3.5	3.5	3.5	3.5	3.5	3.5	3.5	3.5	3.5	3.5
YES	ylinerwater-LD1L	●	0	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2
YES	ylinerwater-LD2L	●	0	2.5	2.5	2.5	2.5	2.5	2.5	2.5	2.5	2.5	2.5	2.5	2.5	2.5	2.5	2.5	2.5	2.5	2.5	2.5	2.5	2.5	2.5	2.5	2.5	2.5	2.5	2.5	2.5	2.5	2.5	2.5	2.5	2.5	2.5	2.5
YES	ylinerwater-HD1L	●	0	2.5	2.5	2.5	2.5	2.5	2.5	2.5	2.5	2.5	2.5	2.5	2.5	2.5	2.5	2.5	2.5	2.5	2.5	2.5	2.5	2.5	2.5	2.5	2.5	2.5	2.5	2.5	2.5	2.5	2.5	2.5	2.5	2.5	2.5	2.5
YES	ylinerwater-HD2L	●	0	2.5	2.5	2.5	2.5	2.5	2.5	2.5	2.5	2.5	2.5	2.5	2.5	2.5	2.5	2.5	2.5	2.5	2.5	2.5	2.5	2.5	2.5	2.5	2.5	2.5	2.5	2.5	2.5	2.5	2.5	2.5	2.5	2.5	2.5	2.5

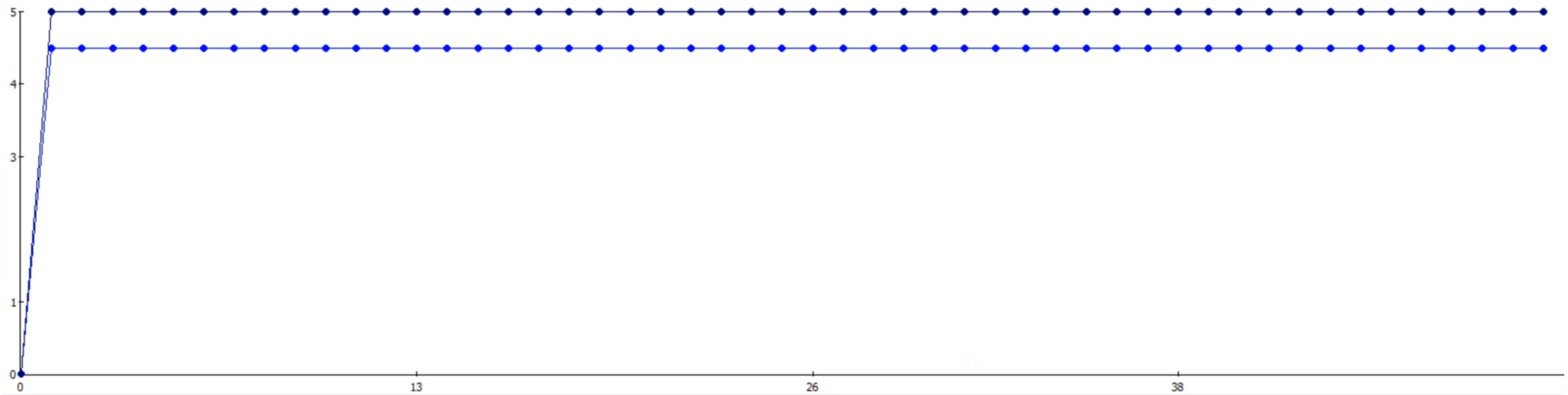
Figure 8.82: *Sample water repair time curve*



Show	Name		0	1	2	3	4	5	6	7	8	9	10	11	12
YES	yRDSR-HD1$	●	0	650.5	672.96	695.42	717.88	740.34	762.8	785.26	807.71	830.17	852.63	875.09	897.55
YES	yRDSR-HD2$	●	0	1337	1383.18	1429.37	1475.55	1521.73	1567.92	1614.1	1660.29	1706.47	1752.65	1798.84	1845.02

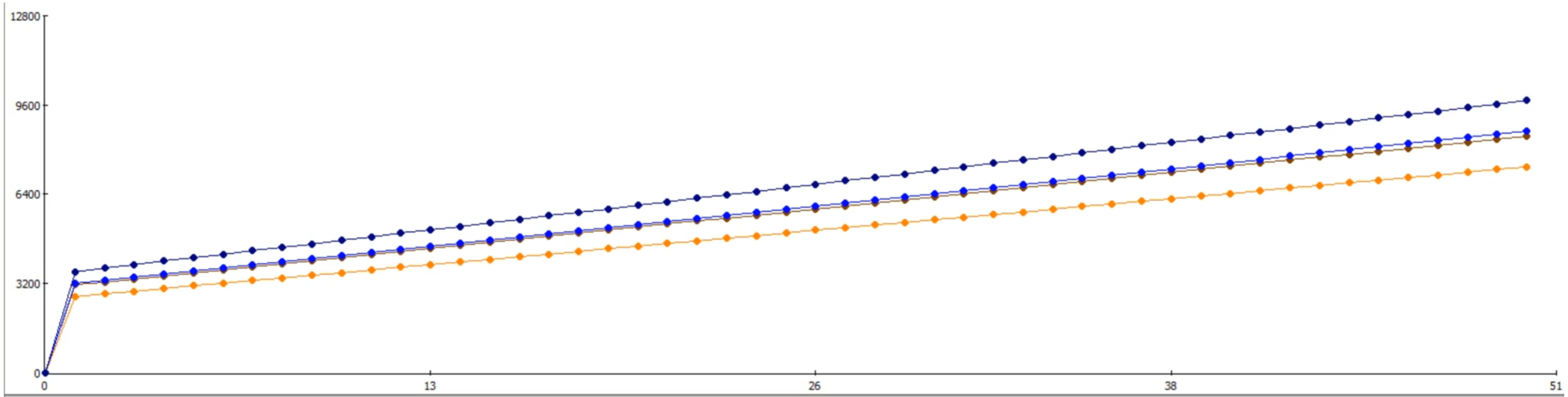
Show	Name	13	14	15	16	17	18	19	20	21	22	23	24	25	
YES	yRDSR-HD1$	920.01	942.47	964.93	987.39	1009.85	1032.31	1054.77	1077.22	1099.68	1122.14	1144.6	1167.06	1189.52	12
YES	yRDSR-HD2$	1891.2	1937.39	1983.57	2029.76	2075.94	2122.12	2168.31	2214.49	2260.67	2306.86	2353.04	2399.22	2445.41	24

Figure 8.83: *Sample partial coordination (roads and sewer) repair cost curve*



Show	Name		0	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30	31	32	33	34	35	36
YES	yRDSR-LD1L	●	0	4.5	4.5	4.5	4.5	4.5	4.5	4.5	4.5	4.5	4.5	4.5	4.5	4.5	4.5	4.5	4.5	4.5	4.5	4.5	4.5	4.5	4.5	4.5	4.5	4.5	4.5	4.5	4.5	4.5	4.5	4.5	4.5	4.5	4.5	4.5	4.5
YES	yRDSR-LD2L	●	0	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5
YES	yRDSR-HD1L	●	0	4.5	4.5	4.5	4.5	4.5	4.5	4.5	4.5	4.5	4.5	4.5	4.5	4.5	4.5	4.5	4.5	4.5	4.5	4.5	4.5	4.5	4.5	4.5	4.5	4.5	4.5	4.5	4.5	4.5	4.5	4.5	4.5	4.5	4.5	4.5	4.5
YES	yRDSR-HD2L	●	0	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5

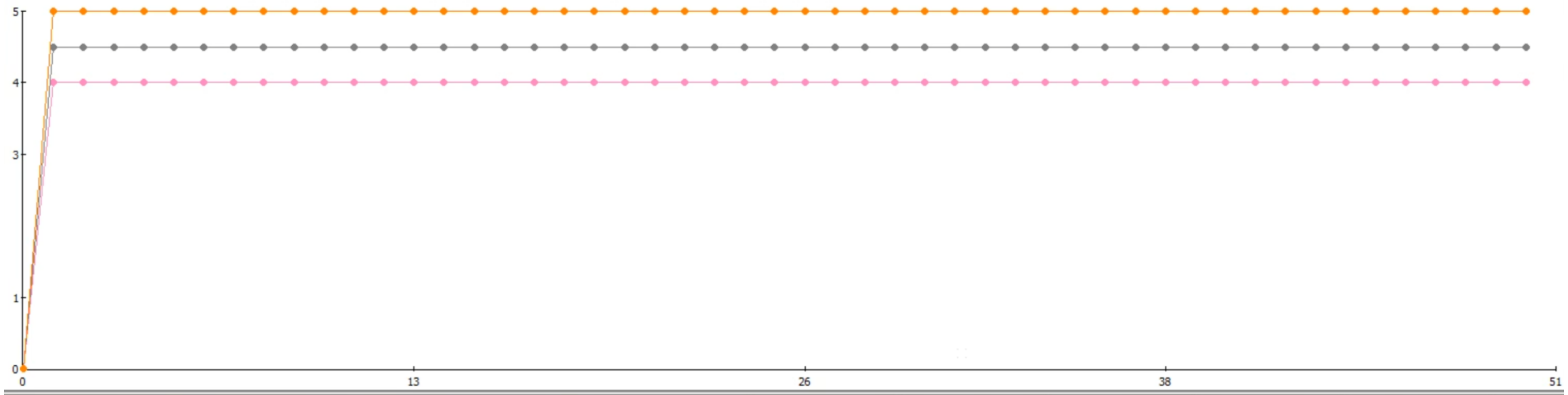
Figure 8.84: *Sample partial coordination (roads and sewer) repair time curve*



Show	Name		0	1	2	3	4	5	6	7	8	9	10	11	12
YES	yRWS-LD1-HD1$	●	0	2742.81	2837.5	2932.19	3026.87	3121.56	3216.25	3310.94	3405.63	3500.31	3595	3689.69	3784.38
YES	yRWS-LD1-HD2$	●	0	3154.95	3263.87	3372.78	3481.7	3590.61	3699.53	3808.45	3917.36	4026.28	4135.2	4244.11	4353.03
YES	yRWS-LD2-HD1$	●	0	3214.83	3325.81	3436.8	3547.78	3658.76	3769.74	3880.73	3991.71	4102.69	4213.68	4324.66	4435.64
YES	yRWS-LD2-HD2$	●	0	3626.97	3752.18	3877.39	4002.6	4127.81	4253.03	4378.24	4503.45	4628.66	4753.87	4879.08	5004.29

Show	Name		13	14	15	16	17	18	19	20	21	22	23	24	25
YES	yRWS-LD1-HD1$	●	3879.07	3973.75	4068.44	4163.13	4257.82	4352.51	4447.19	4541.88	4636.57	4731.26	4825.95	4920.63	5015.32
YES	yRWS-LD1-HD2$	●	4461.94	4570.86	4679.78	4788.69	4897.61	5006.52	5115.44	5224.36	5333.27	5442.19	5551.1	5660.02	5768.94
YES	yRWS-LD2-HD1$	●	4546.62	4657.61	4768.59	4879.57	4990.56	5101.54	5212.52	5323.5	5434.49	5545.47	5656.45	5767.44	5878.42
YES	yRWS-LD2-HD2$	●	5129.5	5254.71	5379.92	5505.14	5630.35	5755.56	5880.77	6005.98	6131.19	6256.4	6381.61	6506.82	6632.03

Figure 8.85: *Sample full coordination (roads, water, and sewer) repair cost curve*



Show	Name		0	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30	31	32	33	34	35	36
YES	yRWS-LD1-LD1L		0	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4
YES	yRWS-LD1-LD2L		0	4.5	4.5	4.5	4.5	4.5	4.5	4.5	4.5	4.5	4.5	4.5	4.5	4.5	4.5	4.5	4.5	4.5	4.5	4.5	4.5	4.5	4.5	4.5	4.5	4.5	4.5	4.5	4.5	4.5	4.5	4.5	4.5	4.5	4.5	4.5	4.5
YES	yRWS-LD2-LD1L		0	4.5	4.5	4.5	4.5	4.5	4.5	4.5	4.5	4.5	4.5	4.5	4.5	4.5	4.5	4.5	4.5	4.5	4.5	4.5	4.5	4.5	4.5	4.5	4.5	4.5	4.5	4.5	4.5	4.5	4.5	4.5	4.5	4.5	4.5	4.5	4.5
YES	yRWS-LD2-LD2L		0	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5
YES	yRWS-HD1-HD1L		0	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4
YES	yRWS-HD1-HD2L		0	4.5	4.5	4.5	4.5	4.5	4.5	4.5	4.5	4.5	4.5	4.5	4.5	4.5	4.5	4.5	4.5	4.5	4.5	4.5	4.5	4.5	4.5	4.5	4.5	4.5	4.5	4.5	4.5	4.5	4.5	4.5	4.5	4.5	4.5	4.5	4.5
YES	yRWS-HD2-HD1L		0	4.5	4.5	4.5	4.5	4.5	4.5	4.5	4.5	4.5	4.5	4.5	4.5	4.5	4.5	4.5	4.5	4.5	4.5	4.5	4.5	4.5	4.5	4.5	4.5	4.5	4.5	4.5	4.5	4.5	4.5	4.5	4.5	4.5	4.5	4.5	4.5
YES	yRWS-HD2-HD2L		0	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5
YES	yRWS-LD1-HD1L		0	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4
YES	yRWS-LD1-HD2L		0	4.5	4.5	4.5	4.5	4.5	4.5	4.5	4.5	4.5	4.5	4.5	4.5	4.5	4.5	4.5	4.5	4.5	4.5	4.5	4.5	4.5	4.5	4.5	4.5	4.5	4.5	4.5	4.5	4.5	4.5	4.5	4.5	4.5	4.5	4.5	4.5
YES	yRWS-LD2-HD1L		0	4.5	4.5	4.5	4.5	4.5	4.5	4.5	4.5	4.5	4.5	4.5	4.5	4.5	4.5	4.5	4.5	4.5	4.5	4.5	4.5	4.5	4.5	4.5	4.5	4.5	4.5	4.5	4.5	4.5	4.5	4.5	4.5	4.5	4.5	4.5	4.5
YES	yRWS-LD2-HD2L		0	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5
YES	yRWS-HD1-LD1L		0	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4
YES	yRWS-HD1-LD2L		0	4.5	4.5	4.5	4.5	4.5	4.5	4.5	4.5	4.5	4.5	4.5	4.5	4.5	4.5	4.5	4.5	4.5	4.5	4.5	4.5	4.5	4.5	4.5	4.5	4.5	4.5	4.5	4.5	4.5	4.5	4.5	4.5	4.5	4.5	4.5	4.5
YES	yRWS-HD2-LD1L		0	4.5	4.5	4.5	4.5	4.5	4.5	4.5	4.5	4.5	4.5	4.5	4.5	4.5	4.5	4.5	4.5	4.5	4.5	4.5	4.5	4.5	4.5	4.5	4.5	4.5	4.5	4.5	4.5	4.5	4.5	4.5	4.5	4.5	4.5	4.5	4.5
YES	yRWS-HD2-LD2L		0	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5

Figure 8.86: *Sample full coordination (roads, water, and sewer) repair time curve*

8.4 Appendix D: Town of Kindersley Schedule Results

8.4.1 *Scenario 1 (Conventional roads)*

Table 8-27: *Schedule of intervention actions (number) and distribution across the planning horizon (Scenario 1 – with crack sealing)*

Action/Period	1	2	3	5	7	9	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	Total	Distribution
Crack Sealing	20		28		26		26	26			26	52	26		52		52	26	52		54	466	61%
Micro-Surfacing	5	1	23	4														26	8		36	103	13%
Patching						13																13	2%
Reconstruction				19					4	9	10	22	13	26	27	9	17	2	17	9		184	24%
Total	25	1	51	23	26	13	26	26	4	9	36	74	39	26	79	9	69	54	77	9	90	766	100%

Table 8-28: *Intervention actions space consumption (m^2) across the planning horizon (Scenario 1 – with crack sealing)*

Action/Period	1	2	3	5	7	9	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	Total	Distribution
Crack Sealing	6,105		13,782		2,647		529	2,118			106	847	1,694		106		1,017	1,355	106		2,341	32,753	35%
Micro-Surfacing	1,493	236	7,205	684														169	1,840		5,457	17,085	18%
Patching						3,027																3,027	3%
Reconstruction				11,465					1,840	2,945	3,836	3,464	2,722	2,677	2,531	2,246	2,983	437	1,153	1,303		39,602	43%
Total	7,598	236	20,987	12,149	2,647	3,027	529	2,118	1,840	2,945	3,942	4,311	4,416	2,677	2,637	2,246	4,000	1,961	3,099	1,303	7,798	92,467	100%

Table 8-29: *Intervention actions distribution among the corridors (Scenario 1 – with crack sealing)*

Corridor #/Action	Crack Sealing	Micro-Surfacing	Patching	Reconstruction	# of interventions
1		1		2	3
101	17	1			18
102		1	1	2	4
103	1			2	3
104		1	1	2	4
106	1			2	3
107	1			2	3
108		1	1	2	4
109		1		2	3
110	1			2	3
111		1		2	3
112		1		2	3
113		1		2	3
115		1		2	3
116		1		2	3
117	1	1		3	5
118	2			4	6
120	17	1			18
121		2		1	3
123		2		1	3
124				1	1
125		1		2	3
126		4		2	6
127		1	1	2	4
128	17	1			18
129	17	1			18
13	1	1		3	5
130		2		1	3
131	1			2	3
133	1			2	3
134	1			2	3
135	1		1	2	4
136		2		1	3
137		1	1	3	5
138		1		2	3
139		2		1	3
140		1	1	2	4
142		1	1	2	4
143		1	1	2	4
147	1			2	3
148		1		2	3
149				1	1
150		1		2	3
153				1	1
154	1			2	3
158				1	1
159	17	1			18
162				1	1
164		2		1	3
167	17	1			18
168		2		1	3
169	17	1			18
171	17	1			18
174				1	1
176	17	1			18
177	17	1			18
179	17	1			18

Corridor #/Action	Crack Sealing	Micro-Surfacing	Patching	Reconstruction	# of interventions
185	17	1			18
186	17	1			18
188	17	1			18
189	17	1			18
190	1	1		3	5
194		2		1	3
197		1		2	3
199	19	1		1	21
20				2	2
201		2		1	3
205		1		2	3
206	1			2	3
207	1			3	4
21				2	2
210	17	1			18
214				2	2
215		2		1	3
216				2	2
221		2		1	3
222		2		1	3
226				2	2
228		2		1	3
230				2	2
232				2	2
241				2	2
243				2	2
244				2	2
245				2	2
255				2	2
256				2	2
258				3	3
259				2	2
262		2		1	3
265				2	2
27		4		2	6
32				2	2
33				2	2
34				2	2
37	17	1			18
40	17	1			18
45		1	1	3	5
46	1	1		4	6
47	17	1			18
49		2		1	3
5	17	1			18
52				2	2
55	17	1			18
61	17	1			18
64		2		1	3
68		1	1	2	4
69	1			2	3
70	1			2	3
75				2	2
76		1		2	3
77		1		2	3
78		2		1	3
81	17	1			18
83	1			2	3
84		1	1	2	4

Corridor #/Action	Crack Sealing	Micro-Surfacing	Patching	Reconstruction	# of interventions
86				1	1
88	1			2	3
89				1	1
90		1		2	3
91		1	1	2	4
93	17	1			18
94	17	1			18
95		1		2	3
96		2		1	3
# of interventions	466	103	13	184	766

Table 8-30: *Intervention actions distribution across the planning horizon (Scenario 1 – with crack sealing)*

Corridor #/Period	1	2	3	5	7	9	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	# of interventions
1		1										1		1								3
101			1		1		1	1			1	2	1		2		2	2	2		2	18
102			1			1								1					1			4
103	1											1		1								3
104			1			1									1				1			4
106	1														1	1						3
107	1											1			1							3
108			1			1								1					1			4
109			1												1		1					3
110	1											1			1							3
111			1											1			1					3
112	1												1		1							3
113			1											1			1					3
115	1												1		1							3
116			1												1		1					3
117	1			1										1			1		1			5
118	1		1									1			1		1	1				6
120			1		1		1	1			1	2	1		2		2	2	2		2	18
121											1										2	3
123											1										2	3
124													1									1
125			1											1			1					3
126									1		1								2		2	6
127			1			1								1					1			4
128			1		1		1	1			1	2	1		2		2	2	2		2	18
129			1		1		1	1			1	2	1		2		2	2	2		2	18
13	1			1										1			1		1			5
130											1										2	3
131	1														1	1						3
133	1														1	1						3
134	1														1	1						3
135			1			1												1	1			4
136											1										2	3
137			1			1									1		1		1			5
138			1												1		1					3
139											1										2	3

Corridor #/Period	1	2	3	5	7	9	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	# of interventions
140			1			1								1					1			4
142			1			1								1					1			4
143			1			1								1					1			4
147	1														1	1						3
148			1												1		1					3
149													1									1
150			1											1			1					3
153													1									1
154	1											1		1								3
158													1									1
159			1		1		1	1			1	2	1		2		2	2	2		2	18
162													1									1
164											1										2	3
167			1		1		1	1			1	2	1		2		2	2	2		2	18
168										1											2	3
169			1		1		1	1			1	2	1		2		2	2	2		2	18
171			1		1		1	1			1	2	1		2		2	2	2		2	18
174														1								1
176			1		1		1	1			1	2	1		2		2	2	2		2	18
177			1		1		1	1			1	2	1		2		2	2	2		2	18
179			1		1		1	1			1	2	1		2		2	2	2		2	18
185			1		1		1	1			1	2	1		2		2	2	2		2	18
186			1		1		1	1			1	2	1		2		2	2	2		2	18
188			1		1		1	1			1	2	1		2		2	2	2		2	18
189			1		1		1	1			1	2	1		2		2	2	2		2	18
190	1			1										1			1		1			5
194										1											2	3
197	1												1		1							3
199			1		1		1	1			2	2	1		2		2	2	2		4	21
20				1								1										2
201										1											2	3
205			1											1			1					3
206	1											1		1								3
207	1											1			1	1						4
21				1																1		2
210			1		1		1	1			1	2	1		2		2	2	2		2	18
214				1								1										2
215										1											2	3

Corridor #/Period	1	2	3	5	7	9	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	# of interventions
216				1																1		2
221									1										2			3
222									1										2			3
226				1								1										2
228										1											2	3
230				1								1										2
232				1																1		2
241				1								1										2
243				1								1										2
244				1								1										2
245				1																1		2
255				1								1										2
256				1																1		2
258				1								1								1		3
259				1																1		2
262										1											2	3
265				1																1		2
27										1	1										4	6
32				1								1										2
33				1																1		2
34				1								1										2
37			1		1		1	1			1	2	1		2		2	2	2		2	18
40			1		1		1	1			1	2	1		2		2	2	2		2	18
45			1			1								1	1				1			5
46	1			1											1	1	1		1			6
47			1		1		1	1			1	2	1		2		2	2	2		2	18
49										1											2	3
5			1		1		1	1			1	2	1		2		2	2	2		2	18
52													1	1								2
55			1		1		1	1			1	2	1		2		2	2	2		2	18
61			1		1		1	1			1	2	1		2		2	2	2		2	18
64										1											2	3
68			1			1									1				1			4
69	1											1			1							3
70	1														1	1						3
75												1		1								2
76	1												1	1								3
77	1												1		1							3

Corridor #/Period	1	2	3	5	7	9	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	# of interventions
78									1										2			3
81			1		1		1	1			1	2	1		2		2	2	2		2	18
83	1											1			1							3
84			1			1									1				1			4
86													1									1
88	1													1		1						3
89													1									1
90			1												1		1					3
91			1			1								1					1			4
93			1		1		1	1			1	2	1		2		2	2	2		2	18
94			1		1		1	1			1	2	1		2		2	2	2		2	18
95			1											1			1					3
96											1										2	3
# of interventions	25	1	51	23	26	13	26	26	4	9	36	74	39	26	79	9	69	54	77	9	90	766

Table 8-31: *Schedule of intervention actions (number) and distribution across the planning horizon (Scenario 1 – without crack sealing)*

Action/Period	1	2	3	4	5	6	8	9	11	13	14	15	16	17	18	19	20	21	22	23	24	25	Total	Distribution
Micro-Surfacing	1	6	21	4		5	12	10	1			12					30		14	28	32	29	205	46.17%
Patching	1							13		19			3										36	8.11%
Reconstruction			1		19						14		6	8	20	24	12	7	23	14	12	34	194	43.69%
Resurfacing														8	1								9	2.03%
Total	2	6	22	4	19	5	12	23	1	19	14	12	9	16	21	24	42	7	37	42	44	63	444	100.00%

Table 8-32: *Intervention actions space consumption (m^2) across the planning horizon (Scenario 1 – without crack sealing)*

Action/Period	1	2	3	4	5	6	8	9	11	13	14	15	16	17	18	19	20	21	22	23	24	25	Total	Distribution
Micro-Surfacing	139	1,590	6,155	1,050		3,929	3,938	2,804	363			5,230					5,605		1,028	4,913	2,496	1,845	41,085	45.28%
Patching	233							2,882		2,293			375										5,783	6.37%
Reconstruction			454		11,465						5,139		1,518	2,392	3,916	2,528	1,871	1,653	1,298	907	788	7,153	41,082	45.28%
Resurfacing														2,494	291								2,785	3.07%
Total	372	1,590	6,609	1,050	11,465	3,929	3,938	5,686	363	2,293	5,139	5,230	1,893	4,886	4,207	2,528	7,476	1,653	2,326	5,820	3,284	8,998	90,735	100.00%

Table 8-33: *Intervention actions distribution among the corridors (Scenario 1 – without crack sealing)*

Corridor #/Action	Micro-Surfacing	Patching	Reconstruction	Resurfacing	# of interventions
1	2		2		4
101	2	1			3
102	2	1	2		5
103	2		2		4
104	3	1	4		8
106	1		1		2
107	2		2		4
108	2		2		4
109	1		2		3
110	2		2		4
111	2		2		4
112	2		2		4
113	2	1	2		5
115	2		2		4
116	2		2		4
117	2		2		4
118	1		1		2
120	3				3
121	2		1		3
123	5	1	3		9
124	2		1		3
125	2	1	2		5
126	2		1		3
127	2	1	2		5
128	3				3
129	3				3
13	2		2		4
130	2		1		3
131	1		1		2
133	1		1		2
134	1		1		2
135	2		2		4
136	2		1		3
137	2		2		4
138	2	1	2		5
139	2		1		3
140	2		3		5
142	2		2		4
143	2	1	2		5
147	1		1		2
148	2	1	2		5
149	2		1		3
150	2	1	2		5
153	2		1		3
154	2		2		4
158	2		1		3
159	4				4
162			1		1
164	2		1		3
167	4		1		5
168	2		1		3
169	1			1	2
171			1		1
174	1		1		2
176			1		1
177			1		1
179	3				3
185	1			1	2
186	1			1	2
188	3	1		1	5
189	1			1	2
190	2		2		4
194	2		1		3
197	2		2		4
199	4				4
20		1	3		4

Corridor #/Action	Micro-Surfacing	Patching	Reconstruction	Resurfacing	# of interventions
201	2		1		3
205	1		2		3
206	1		1		2
207	1		1		2
21		1	3		4
210	3				3
214		1	3		4
215	3		4	1	8
216		1	3		4
221	2		1		3
222	2		1		3
226		1	3		4
228	2		1		3
230		1	3		4
232		1	3		4
241		1	3		4
243		1	3		4
244		1	3		4
245		1	3		4
255		1	3		4
256		1	3		4
258		1	3		4
259		1	3		4
262	2		1		3
265		1	3		4
27	2		1		3
32		1	3		4
33		1	3		4
34		1	3		4
37	3				3
40	1			1	2
45	3		4		7
46	2		2		4
47			1		1
49	2		1		3
5			1		1
52			1		1
55	4		1		5
61	4				4
64	2		1		3
68	2		2		4
69	1		1		2
70	1		1		2
75			1		1
76	2		2		4
77	6		4		10
78	2		1		3
81	3				3
83	1		1		2
84	2	1	2		5
86	2		1		3
88	1		1		2
89	2		1		3
90	2	1	2		5
91	2	1	2		5
93	4	1		1	6
94	1			1	2
95	2	1	2		5
96	2		1		3
# of interventions	205	36	194	9	444

Table 8-34: *Intervention actions distribution across the planning horizon (Scenario 1 – without crack sealing)*

Corridor #/Period	1	2	3	4	5	6	8	9	11	13	14	15	16	17	18	19	20	21	22	23	24	25	# of interventions
1		1													1		1				1		4
101													1				2						3
102			1					1								1				1		1	5
103								1							1						1	1	4
104			1	1				1								1	1		1	1		1	8
106							1														1		2
107								1							1						1	1	4
108			1													1		1				1	4
109				1													1		1				3
110								1							1						1	1	4
111			1													1		1				1	4
112		1													1		1				1		4
113			1					1								1				1		1	5
115		1													1		1				1		4
116			1													1		1				1	4
117								1							1						1	1	4
118							1														1		2
120												1					2						3
121													1							1	1		3
123	1										1		1		1				1	2	2		9
124														1							1	1	3
125			1					1								1				1		1	5
126											1								1	1			3
127			1					1								1				1		1	5
128												1					2						3
129												1					2						3
13								1							1						1	1	4
130													1							1	1		3
131							1														1		2
133							1														1		2
134							1														1		2
135								1							1						1	1	4
136													1							1	1		3
137			1													1		1				1	4
138			1					1								1				1		1	5

Corridor #/Period	1	2	3	4	5	6	8	9	11	13	14	15	16	17	18	19	20	21	22	23	24	25	# of interventions
139													1							1	1		3
140			1													1	1	1				1	5
142			1													1		1				1	4
143			1					1								1				1		1	5
147							1														1		2
148			1					1								1				1		1	5
149														1							1	1	3
150			1					1								1				1		1	5
153														1							1	1	3
154								1							1						1	1	4
158														1							1	1	3
159						1						1					2						4
162														1									1
164													1							1	1		3
167						1						1					2			1			5
168											1								1	1			3
169														1						1			2
171																						1	1
174															1						1		2
176																						1	1
177																						1	1
179												1					2						3
185														1						1			2
186														1						1			2
188													1	1			2			1			5
189														1						1			2
190								1							1						1	1	4
194											1								1	1			3
197		1													1		1				1		4
199						1						1					2						4
20					1					1									1			1	4
201											1								1	1			3
205				1													1		1				3
206							1														1		2
207							1														1		2
21					1					1									1			1	4
210												1					2						3

Corridor #/Period	1	2	3	4	5	6	8	9	11	13	14	15	16	17	18	19	20	21	22	23	24	25	# of interventions
214					1					1									1			1	4
215			1					1	1						3						1	1	8
216					1					1									1			1	4
221											1								1	1			3
222											1								1	1			3
226					1					1									1			1	4
228											1								1	1			3
230					1					1									1			1	4
232					1					1									1			1	4
241					1					1									1			1	4
243					1					1									1			1	4
244					1					1									1			1	4
245					1					1									1			1	4
255					1					1									1			1	4
256					1					1									1			1	4
258					1					1									1			1	4
259					1					1									1			1	4
262											1								1	1			3
265					1					1									1			1	4
27											1								1	1			3
32					1					1									1			1	4
33					1					1									1			1	4
34					1					1									1			1	4
37												1					2						3
40														1						1			2
45			1	1												1	2		1			1	7
46								1							1						1	1	4
47																						1	1
49											1								1	1			3
5																						1	1
52																1							1
55						1						1			1		2						5
61						1						1					2						4
64											1								1	1			3
68			1													1		1				1	4
69							1														1		2
70							1														1		2

Corridor #/Period	1	2	3	4	5	6	8	9	11	13	14	15	16	17	18	19	20	21	22	23	24	25	# of interventions
75																1							1
76		1													1		1				1		4
77	1	1												1	1	1	1				2	2	10
78											1								1	1			3
81												1					2						3
83							1														1		2
84			1					1								1				1		1	5
86														1							1	1	3
88							1														1		2
89														1							1	1	3
90			1					1								1				1		1	5
91			1					1								1				1		1	5
93													1	1			2			1	1		6
94														1						1			2
95			1					1								1				1		1	5
96											1								1	1			3
# of interventions	2	6	22	4	19	5	12	23	1	19	14	12	9	16	21	24	42	7	37	42	44	63	444

8.4.2 *Scenario 2 (Conventional water)*

Table 8-35: *Schedule of intervention actions (number) and distribution across the planning horizon (Scenario 2)*

Action/Period	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	Total	Distribution
Pipe lining (Low demand + Same diameter)																				1	1				1	3	1%
Pipe replacement (High demand + Same diameter)	3	2	2	2	8	3	3		2	7	2	3	1	2	7	2	2	1	3	11	6	6	7	7	14	106	35%
Pipe replacement (Low demand + Same diameter)	5	7	5	7	13	4	6	4	6	13	4	4	2	5	11	5	3	2	5	12	3	3	7	13	14	163	54%
Pipe replacement (Low demand + Bigger diameter)											1		2						3	5	5	6	3	2	4	31	10%
Total	8	9	7	9	21	7	9	4	8	20	7	7	5	7	18	7	5	3	11	29	15	15	17	22	33	303	100%

Table 8-36: *Intervention actions space consumption (m^2) across the planning horizon (Scenario 2)*

Action/Period	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	Total	Distribution
Pipe lining (Low demand + Same diameter)																				40	687				40	767	1%
Pipe replacement (High demand + Same diameter)	2,518	1,085	2,066	620	4,609	2,518	1,461		620	4,373	2,253	1,461	265	620	4,373	2,253	752	265	1,000	6,035	4,386	2,881	2,045	2,129	6,691	57,279	43%
Pipe replacement (Low demand + Same diameter)	2,543	2,698	1,925	3,583	5,239	1,804	2,468	1,544	3,345	5,239	1,761	1,852	762	2,652	3,631	2,190	1,401	762	1,668	4,040	847	2,268	2,740	4,117	4,287	65,366	49%
Pipe replacement (Low demand + Bigger diameter)											429		792						808	1,586	1,542	2,273	786	1,202	1,516	10,934	8%
Totals	5,061	3,783	3,991	4,203	9,848	4,322	3,929	1,544	3,965	9,612	4,443	3,313	1,819	3,272	8,004	4,443	2,153	1,027	3,476	11,701	7,462	7,422	5,571	7,448	12,534	134,346	100%

Table 8-37: *Intervention actions distribution among the corridors (Scenario 2)*

Corridor #/Action	Pipelining (Low demand + Same diameter)	Pipe replacement (High demand + Same diameter)	Pipe replacement (Low demand + Same diameter)	Pipe replacement (Low demand + Bigger diameter)	# of interventions
1			1		1
101		4			4
102			1		1
103			3		3
104		4			4
106		1			1
107		5			5
108			4		4
109			4		4
110			4		4
111			4		4
112			2		2
113		1			1
115		5			5
116		4			4
117			3		3
118			3		3
120		1			1
121		1			1
123			1		1
124		1			1
125		1			1
126			1	1	2
127				1	1
128		1			1
129			1		1
13			4		4
130			1	2	3
131		1			1
133				1	1
134			1	1	2
135		1			1
136			1	1	2
137			2		2
138			5		5
139			4		4
140			5		5
142			4		4
143		1			1
147		2			2
148			2		2
149			1	1	2
150			4		4
153				1	1
154				1	1
158				1	1
159				1	1
162		2			2
164		1			1
167			2		2
168			1		1
169		1			1
171			2		2
174		1			1

Corridor #/Action	Pipelining (Low demand + Same diameter)	Pipe replacement (High demand + Same diameter)	Pipe replacement (Low demand + Same diameter)	Pipe replacement (Low demand + Bigger diameter)	# of interventions
176			4		4
177			4		4
179			4		4
185		5			5
186			4		4
188			1		1
189			1		1
190			4		4
194			2		2
197				1	1
199		5			5
20			4		4
201			1		1
205			3		3
206			1	1	2
207		1			1
21		4			4
210			1		1
214			1		1
215			1	2	3
216	3				3
221			5		5
222		5			5
226			1		1
228		1			1
230			3		3
232		4			4
241				1	1
243		5			5
244			2	1	3
245		5			5
255		3			3
256			2		2
258		2			2
259			2	1	3
262				1	1
265			3		3
27			2		2
32				1	1
33			2	1	3
34		3			3
37			3		3
40				1	1
45			5		5
46		4			4
47		2			2
49		1			1
5				1	1
52		1			1
55				2	2
61		1			1
64			4		4
68			4		4
69		1			1
70			5		5
75			4		4
76		1			1

Corridor #/Action	Pipelining (Low demand + Same diameter)	Pipe replacement (High demand + Same diameter)	Pipe replacement (Low demand + Same diameter)	Pipe replacement (Low demand + Bigger diameter)	# of interventions
77			1	1	2
78		1			1
81			2		2
83				1	1
84			1		1
86		4			4
88			5		5
89		1			1
90		2			2
91				1	1
93				1	1
94		4			4
95				1	1
96		1			1
# of interventions	3	106	163	31	303

Table 8-38: *Intervention actions distribution across the planning horizon (Scenario 2)*

Corridor #/Period	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	# of interventions
1																									1	1
101					1					1					1					1						4
102				1																						1
103					1					1					1											3
104					1					1					1					1						4
106																									1	1
107				1					1					1					1					1		5
108					1					1					1					1						4
109					1					1					1					1						4
110				1					1					1					1							4
111				1					1					1										1		4
112		1					1																			2
113																								1		1
115	1					1							1					1							1	5
116		1					1					1					1									4
117		1					1																		1	3
118			1					1																	1	3
120																							1			1
121																							1			1
123																							1			1
124																									1	1
125																							1			1
126																				1					1	2
127																							1			1
128																							1			1
129																							1			1
13					1					1					1					1						4
130																				1		1			1	3
131																						1				1
133																							1			1
134																				1					1	2
135																									1	1
136																			1					1		2
137			1																					1		2
138	1					1					1					1					1					5

Corridor #/Period	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	# of interventions
139			1					1					1					1								4
140		1					1					1					1					1				5
142					1					1					1					1						4
143					1																					1
147																			1						1	2
148																			1					1		2
149																				1					1	2
150		1									1					1					1					4
153																						1				1
154																					1					1
158																					1					1
159																						1				1
162																				1					1	2
164																						1				1
167				1					1																	2
168																								1		1
169																								1		1
171					1					1																2
174																								1		1
176				1					1					1								1				4
177		1					1					1					1									4
179					1					1					1					1						4
185				1					1					1					1					1		5
186					1					1					1					1						4
188																								1		1
189																					1					1
190					1					1					1					1						4
194																			1					1		2
197																									1	1
199	1					1					1					1					1					5
20					1					1					1					1						4
201																								1		1
205					1					1					1											3
206																				1					1	2
207																							1			1
21					1					1					1					1						4
210																									1	1

Corridor #/Period	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	# of interventions
214																									1	1
215																			1		1			1		3
216																				1	1				1	3
221	1					1					1					1						1				5
222	1					1					1					1					1					5
226																							1			1
228																					1					1
230	1					1																	1			3
232		1					1					1										1				4
241																					1					1
243					1					1					1					1					1	5
244													1							1					1	3
245					1					1					1					1					1	5
255																				1					2	3
256			1					1																		2
258			1																		1					2
259													1							1					1	3
262																						1				1
265					1					1													1			3
27	1																							1		2
32																								1		1
33											1					1							1			3
34																				1				1	1	3
37		1					1					1														3
40																						1				1
45				1					1					1					1					1		5
46							1					1					1					1				4
47			1																						1	2
49																								1		1
5																								1		1
52																						1				1
55																					1		1			2
61																					1					1
64	1					1					1					1										4
68			1					1					1					1								4
69																							1			1
70				1					1					1					1					1		5

Corridor #/Period	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	# of interventions
75					1					1					1					1						4
76																									1	1
77																			1					1		2
78																						1				1
81																				1					1	2
83																									1	1
84																									1	1
86					1					1					1					1						4
88		1					1					1					1						1			5
89																							1			1
90																				1					1	2
91																						1				1
93																									1	1
94					1					1					1					1						4
95																									1	1
96																					1					1
# of interventions	8	9	7	9	21	7	9	4	8	20	7	7	5	7	18	7	5	3	11	29	15	15	17	22	33	303

8.4.3 *Scenario 3 (Conventional sewer)*

Table 8-39: *Schedule of intervention actions (number) and distribution across the planning horizon (Scenario 3)*

Action/Period	17	18	19	20	21	22	23	24	25	Total	Distribution
Pipelining (High demand + same diameter)					5	1		1	4	11	6%
Pipelining (Low demand + Same diameter)			3	1	5	1		3	4	17	9%
Pipe replacement (High demand + Bigger diameter)		11	7	5	3	4	2	5	24	61	31%
Pipe replacement (Low demand + Same diameter)	5	14	6	12	3	9	9	8	42	108	55%
Total	5	25	16	18	16	15	11	17	74	197	100%

Table 8-40: *Intervention actions space consumption (m^2) across the planning horizon (Scenario 3)*

Action/Period	17	18	19	20	21	22	23	24	25	Total	Distribution
Pipelining (High demand + same diameter)					2,692	473		225	2,082	5,472	7%
Pipelining (Low demand + Same diameter)			1,497	451	3,177	738		2,275	2,470	10,608	14%
Pipe replacement (High demand + Bigger diameter)		3,254	2,163	1,594	1,167	1,069	607	1,144	6,994	17,992	24%
Pipe replacement (Low demand + Same diameter)	1,599	4,562	1,555	4,394	2,085	3,152	5,431	3,425	13,761	39,964	54%
Total	1,599	7,816	5,215	6,439	9,121	5,432	6,038	7,069	25,307	74,036	100%

Table 8-41: *Intervention actions distribution among the corridors (Scenario 3)*

Corridor #/Action	Pipelining (High demand + same diameter)	Pipelining (Low demand + Same diameter)	Pipe replacement (High demand + Bigger diameter)	Pipe replacement (Low demand + Same diameter)	# of interventions
1	1				1
101				1	1
102				1	1
103			1		1
104				2	2
106				2	2
107				2	2
108				1	1
109			1		1
110				1	1
111			1		1
112			1		1
113				1	1
115				2	2
116				2	2
117				2	2
118			2		2
120				2	2
121				2	2
123				4	4
124				2	2
125				2	2
126				2	2
127			2		2
128				2	2
129				2	2
13			2		2
130				2	2
131				2	2
133				2	2
134				2	2
135				2	2
136			2		2
137				2	2
138			2		2
139			2		2
140			2		2
142			2		2
143				2	2
147				2	2
148			2		2
149				2	2
150				2	2
153			1		1
154				2	2
158			4		4
159				1	1
162				2	2
164				2	2
167				2	2
168			2		2
169				2	2
171				1	1
174				2	2
176		1			1
177		1			1

Corridor #/Action	Pipelining (High demand + same diameter)	Pipelining (Low demand + Same diameter)	Pipe replacement (High demand + Bigger diameter)	Pipe replacement (Low demand + Same diameter)	# of interventions
179	1				1
185				1	1
186			1		1
188				1	1
189				1	1
190			2		2
194				2	2
197				1	1
199				1	1
20	1				1
201			1		1
205				1	1
206				1	1
207				2	2
21		1			1
210				1	1
214				1	1
215			1		1
216			2		2
221			2		2
222				1	1
226			1		1
228				1	1
230		2			2
232				1	1
241		1		1	2
243		2			2
244			1		1
245				1	1
255				1	1
256		1			1
258				1	1
259				1	1
262			1		1
265	1		2		3
27	1				1
32		1			1
33		1			1
34		1			1
37		1		1	2
40	1				1
45	1				1
46		1			1
47				1	1
49				1	1
5	1				1
52		1			1
55				1	1
61		1			1
64	1				1
68	1				1
69		1			1
70	1				1
75			4		4
76				1	1
77			2		2
78				2	2
81			2		2
83			2		2

Corridor #/Action	Pipelining (High demand + same diameter)	Pipelining (Low demand + Same diameter)	Pipe replacement (High demand + Bigger diameter)	Pipe replacement (Low demand + Same diameter)	# of interventions
84			2		2
86				1	1
88			2		2
89				2	2
90				2	2
91				2	2
93			2		2
94				2	2
95			2		2
96				2	2
# of interventions	11	17	61	108	197

Table 8-42: *Intervention actions distribution across the planning horizon (Scenario 3)*

Corridor #/Period	17	18	19	20	21	22	23	24	25	# of interventions
1									1	1
101								1		1
102						1				1
103								1		1
104						1		1		2
106				1					1	2
107				1					1	2
108								1		1
109								1		1
110								1		1
111								1		1
112						1				1
113								1		1
115			1						1	2
116			1						1	2
117		1							1	2
118		1							1	2
120		1							1	2
121				1					1	2
123	1		1						2	4
124				1					1	2
125		1							1	2
126	1								1	2
127		1							1	2
128		1							1	2
129		1							1	2
13			1						1	2
130			1						1	2
131		1							1	2
133				1					1	2
134				1					1	2
135		1							1	2
136			1						1	2
137				1					1	2
138				1					1	2
139				1					1	2
140			1						1	2
142		1							1	2
143		1							1	2
147		1							1	2
148		1							1	2
149				1					1	2
150		1							1	2
153							1			1
154			1						1	2
158		1		1					2	4
159							1			1
162	1								1	2
164			1						1	2

Corridor #/Period	17	18	19	20	21	22	23	24	25	# of interventions
167				1					1	2
168				1					1	2
169				1					1	2
171							1			1
174		1							1	2
176								1		1
177								1		1
179								1		1
185							1			1
186							1			1
188							1			1
189							1			1
190			1						1	2
194						1	1			2
197							1			1
199							1			1
20					1					1
201									1	1
205									1	1
206									1	1
207				1					1	2
21					1					1
210									1	1
214					1					1
215						1				1
216					1	1				2
221								1	1	2
222								1		1
226					1					1
228					1					1
230			1						1	2
232								1		1
241			1						1	2
243			1						1	2
244					1					1
245								1		1
255						1				1
256									1	1
258						1				1
259						1				1
262						1				1
265			1					1	1	3
27									1	1
32					1					1
33					1					1
34								1		1
37				1					1	2
40					1					1
45									1	1
46					1					1
47					1					1
49						1				1
5					1					1
52						1				1
55							1			1
61									1	1
64						1				1
68					1					1
69					1					1
70					1					1
75			1	1					2	4
76						1				1
77		1							1	2
78	1								1	2
81			1						1	2
83		1							1	2
84		1							1	2
86						1				1
88		1							1	2

Corridor #/Period	17	18	19	20	21	22	23	24	25	# of interventions
89				1					1	2
90		1							1	2
91		1							1	2
93		1							1	2
94		1							1	2
95		1							1	2
96	1								1	2
# of interventions	5	25	16	18	16	15	11	17	74	197

8.4.4 *Scenario 4 (Combined conventional – roads + water + sewer)*

Table 8-43: *Schedule of intervention actions (number) and distribution across the planning horizon (Scenario 4)*

Action/Period	1	12	13	14	15	16	17	18	19	20	21	22	23	24	25	Total	Distribution
Sewer pipe lining (High demand + Same diameter)		4					2	1	3	1		2	3	1	2	19	3%
Sewer pipe lining (Low demand + Same diameter)		2	1			1	1	1	6	2		3	2	2	2	23	4%
Micro-Surfacing	47										7					54	10%
Patching	30									1	3					34	6%
Reconstruction			11	3	16	12	13	14	13							82	15%
Sewer pipe replacement (High demand + Same diameter)			4				1	2	4	10	1	1	5	2	5	35	6%
Sewer pipe replacement (Low demand + Same diameter)			1		3	1			11	17	3	3	3	10	15	67	12%
Water pipe replacement (High demand + Same diameter)				1			1	1	1		13	11	16	21	26	91	16%
Water pipe replacement (Low demand + Same diameter)				1					1		8	25	8	22	38	103	18%
Water pipe replacement (Low demand + Bigger diameter)											8	7	2	7	15	39	7%
Resurfacing		1	4	6				1	1							13	2%
Total	77	7	21	11	19	14	18	20	40	31	43	52	39	65	103	560	100%

Table 8-44: *Intervention actions space consumption (m²) across the planning horizon (Scenario 4)*

Action/Period	1	12	13	14	15	16	17	18	19	20	21	22	23	24	25	Total	Distribution
Sewer pipe lining (High demand + Same diameter)		733					733	25	81	144		825	268	81	861	3,749	3%
Sewer pipe lining (Low demand + Same diameter)		376	429			546	376	429	671	1,193		612	1,019	671	1,193	7,515	6%
Micro-Surfacing	21,211										1,002					22,213	17%
Patching	9,443									152	1,774					11,369	9%
Reconstruction			2,396	621	1,840	2,927	2,723	3,190	2,986							16,683	13%
Sewer pipe replacement (High demand + Same diameter)			665				69	640	497	1,360	211	69	1,489	497	1,499	6,995	5%
Sewer pipe replacement (Low demand + Same diameter)			1,071		1,561	150			1,291	4,063	1,042	629	582	1,479	3,400	15,268	12%
Water pipe replacement (High demand + Same diameter)				1,149			577	1,071	1,149		1,577	1,348	3,782	3,836	5,288	19,777	15%
Water pipe replacement (Low demand + Same diameter)				717					717		854	1,639	1,233	4,483	6,802	16,445	13%
Water pipe replacement (Low demand + Bigger diameter)											832	918	296	981	2,671	5,698	4%
Resurfacing		180	2,390	2,408				36	144							5,158	4%
Total	30,654	1,288	6,951	4,895	3,401	3,623	4,478	5,391	7,536	6,912	7,292	6,040	8,669	12,028	21,714	130,870	100%

Table 8-45: *Intervention actions distribution among the corridors (Scenario 4)*

Corridor #/Action	Sewer pipelining (High demand + Same diameter)	Sewer pipelining (Low demand + Same diameter)	Micro-Surfacing	Patching	Reconstruction	Sewer pipe replacement (High demand + Same diameter)	Sewer pipe replacement (Low demand + Same diameter)	Water pipe replacement (High demand + Same diameter)	Water pipe replacement (Low demand + Same diameter)	Water pipe replacement (Low demand + Bigger diameter)	Resurfacing	# of interventions
1				1					2			3
101			2	1	1		2	4			1	11
102				1	2		3		2			8
103			1		2	3			2			8
104				1	2		3	2				8
106			1		1			3				5
107			1		2			5				8
108				1	3		6		2			12
109				1	2	3			2			8
110			1		2		3		2			8
111				1	2	3			2			8
112				1	2	3			2			8
113				1	2		2	2				7
115				1	2			5				8
116				1	1			3				5
117			2		1		1		4			8
118			2		1	1			4			8
120			1				1	2				4
121								1				1
123									2			2
124							1	1				2
125				1	1			3				5
126										1		1
127				1	1					3		5
128			1		1			3				5
129			1				1		2			4
13			1			4						5
130										2		2
131			1		1		1	3				6
133			1		1					3		5
134			1		1					3		5
135			1		1		1	3				6
136										1		1

Corridor #/Action	Sewer pipelining (High demand + Same diameter)	Sewer pipelining (Low demand + Same diameter)	Micro-Surfacing	Patching	Reconstruction	Sewer pipe replacement (High demand + Same diameter)	Sewer pipe replacement (Low demand + Same diameter)	Water pipe replacement (High demand + Same diameter)	Water pipe replacement (Low demand + Same diameter)	Water pipe replacement (Low demand + Bigger diameter)	Resurfacing	# of interventions
137				1			1		2			4
138				1		1			3			5
139									1			1
140				1	1				3			5
142			1	1	2				6			10
143				1	2			5				8
147			1		2		1	5				9
148				1	1				3			5
149							1			1		2
150				1	1				3			5
153					1	1			1			3
154			1		2		2					5
158						1			1			2
159			1		2		1		1			5
162								1				1
164								1				1
167			1				1		4		1	7
168									1			1
169			1				1	2				4
171			1	2			4		2		4	13
174				1	1			3				5
176		6	1		1						1	9
177		6	1		1						1	9
179	6		1		1						1	9
185			1					3			1	5
186			1			1			2		1	5
188			1		1				3			5
189			1		1				3			5
190			1		2				2			5
194							1		1			2
197				1	1		1			2		5
199			3	1	1		4	1			1	11
20	1								2			3
201									1			1
205				1					2			3

Corridor #/Action	Sewer pipelining (High demand + Same diameter)	Sewer pipelining (Low demand + Same diameter)	Micro-Surfacing	Patching	Reconstruction	Sewer pipe replacement (High demand + Same diameter)	Sewer pipe replacement (Low demand + Same diameter)	Water pipe replacement (High demand + Same diameter)	Water pipe replacement (Low demand + Same diameter)	Water pipe replacement (Low demand + Bigger diameter)	Resurfacing	# of interventions
206			1							3		4
207			1					2				3
21							2	4				6
210			1						2			3
214							1		1			2
215						1				1		2
216						1						1
221									1			1
222								1				1
226						1						1
228							1					1
230										1		1
232								2				2
241										1		1
243								1				1
244						3						3
245								1				1
255							3	1				4
256									2			2
258							3					3
259							3					3
262						2						2
265						1						1
27									1			1
32		1					1					2
33		3										3
34								1				1
37			1							2		3
40	1		1		2				1			5
45				1					2			3
46		4	1									5
47			1		1		4	2				8
49								1				1
5	1		1		2				1			5
52		1			1		1					3

Corridor #/Action	Sewer pipelining (High demand + Same diameter)	Sewer pipelining (Low demand + Same diameter)	Micro-Surfacing	Patching	Reconstruction	Sewer pipe replacement (High demand + Same diameter)	Sewer pipe replacement (Low demand + Same diameter)	Water pipe replacement (High demand + Same diameter)	Water pipe replacement (Low demand + Same diameter)	Water pipe replacement (Low demand + Bigger diameter)	Resurfacing	# of interventions
55			1		1				1	2		5
61			1					2				3
64	1											1
68	3			1					1			5
69		2	1		2							5
70	6		1			1						8
75									2			2
76				1	2		2					5
77				1	2				4	1		8
78								2				2
81			1		2	1			1			5
83			1		1	1				3		6
84				1	1				3			5
86					1		2	1				4
88			2		1	1			4			8
89							1	2				3
90				1	1			3				5
91				1	1					3		5
93			1		1	1				4		7
94			1					3			1	5
95				1	1				1	2		5
96								1				1
# of interventions	19	23	54	34	82	35	67	91	103	39	13	560

Table 8-46: *Intervention actions distribution across the planning horizon (Scenario 4)*

Corridor #/Period	1	12	13	14	15	16	17	18	19	20	21	22	23	24	25	# of interventions
1	1												1	1		3
101	1			1	1					1	2		1	2	2	11
102	1		1		1				2			2		1		8
103	1		1		1				2			2		1		8
104	1		1		1				2			2		1		8
106	1								1		1				2	5
107	1						1	1			1		1	3		8
108	1		1	1	1				2	2		2		1	1	12
109	1			1	1					2		2			1	8
110	1		1		1				2			2		1		8
111	1		1		1				2			2		1		8
112	1			1	1					2		2			1	8
113	1					1	1						2		2	7
115	1							1	1			1		2	2	8
116	1								1			1			2	5
117	1				1					1	1		1		3	8
118	1				1					1	1		1		3	8
120	1									1	1				1	4
121												1				1
123													1	1		2
124										1					1	2
125	1							1			1			2		5
126															1	1
127	1								1			1			2	5
128	1								1		1				2	5
129	1									1	1				1	4
13	1		2					1					1			5
130											1	1				2
131	1							1		1				2	1	6
133	1								1			1			2	5
134	1								1		1				2	5
135	1							1		1				2	1	6
136												1				1
137	1									1		1			1	4
138	1									1	1	1			1	5
139												1				1
140	1								1			1			2	5
142	1				1		1				1	1	1	1	3	10
143	1					1	1				1		2	2		8
147	1						1	1		1			1	3	1	9
148	1							1			1			1	1	5
149										1					1	2
150	1						1				1			1	1	5
153							1						1		1	3
154	1						2						1		1	5
158										1					1	2
159	1						2							1	1	5
162													1			1
164												1				1
167	1			1						1		1		1	2	7
168															1	1
169	1									1		1			1	4
171	1	1	1					1	1		2			2	4	13
174	1								1			1			2	5
176	1		2						3	1				1	1	9
177	1		2						3	1				1	1	9
179	1		2						3	1				1	1	9
185	1			1							1	1	1			5
186	1			1							1	1			1	5
188	1							1			1			2		5
189	1							1			1			2		5
190	1				2							1	1			5
194												1			1	2
197	1					1					1	1	1			5
199	1			1	1						4				4	11
20				1					1						1	3

Corridor #/Period	1	12	13	14	15	16	17	18	19	20	21	22	23	24	25	# of interventions
201														1		1
205	1													2		3
206	1												1	1	1	4
207	1										1		1			3
21				1	1				1	1					2	6
210	1													1	1	3
214												1	1			2
215														1	1	2
216													1			1
221														1		1
222															1	1
226											1					1
228											1					1
230													1			1
232													1	1		2
241															1	1
243													1			1
244			1					1					1			3
245													1			1
255						1	1				1	1				4
256														1	1	2
258					1					1					1	3
259					1					1					1	3
262							1					1				2
265															1	1
27															1	1
32						1					1					2
33			1					1					1			3
34														1		1
37	1										1	1				3
40	1					2							1		1	5
45	1													1	1	3
46	1	2					1					1				5
47	1		2					1	2				1	1		8
49												1				1
5	1					2							1		1	5
52						1							1		1	3
55	1							1			1			2		5
61	1													2		3
64												1				1
68	1	2					1						1			5
69	1					2						2				5
70	1	2	1				1	1				1	1			8
75											1	1				2
76	1					2						1	1			5
77	1							1	1		1			2	2	8
78													1		1	2
81	1						2						1		1	5
83	1							1		1				2	1	6
84	1								1			1			2	5
86			1						1		1			1		4
88	1				1					1	1				4	8
89										1	1				1	3
90	1								1			1			2	5
91	1							1				1		1	1	5
93	1								1	1	1				3	7
94	1			1							1		1	1		5
95	1							1			1			2		5
96															1	1
# of interventions	77	7	21	11	19	14	18	20	40	31	43	52	39	65	103	560

8.4.5 *Scenario 5 (Partially-coordinated – roads and sewer + conventional water)*

Table 8-47: *Schedule of intervention actions (number) and distribution across the planning horizon (Scenario 5)*

Action/Period	12	14	15	16	17	18	19	20	21	22	23	24	25	Total	Distribution
Reconstruction			6	3	1									10	4%
Partial Coordination - Road and sewer (High demand + Bigger diameter)					1	4	4	4	6	5	5	3	10	42	15%
Partial Coordination - Road and sewer (Low demand + Same diameter)					1		3		1	1			4	10	4%
Partial Coordination - Road and sewer (Low demand + Bigger diameter)					3	4	3	8	7	10	15	7	13	70	26%
Water pipe replacement (High demand + Same diameter)				1	2		1		2	2	6	10	15	39	14%
Water pipe replacement (Low demand + Same diameter)		2	2	1			1	4	3	2	5	27	13	60	22%
Water pipe replacement (Low demand + Bigger diameter)			2		1			1	1			2	6	13	5%
Resurfacing	1		13	5	1	2	3	1	1					27	10%
Total	1	2	23	10	10	10	15	18	21	20	31	49	61	271	100%

Table 8-48: *Intervention actions space consumption (m^2) across the planning horizon (Scenario 5)*

Action/Period	12	14	15	16	17	18	19	20	21	22	23	24	25	Total	Distribution
Reconstruction			1,530	800	738									3,068	4%
Partial Coordination - Road and sewer (High demand + Bigger diameter)					376	1,284	1,387	1,219	1,847	1,088	1,301	917	2,090	11,509	13%
Partial Coordination - Road and sewer (Low demand + Same diameter)					376		1,255		47	76			941	2,695	3%
Partial Coordination - Road and sewer (Low demand + Bigger diameter)					539	2,597	1,043	2,314	1,898	3,325	3,976	2,947	3,561	22,200	26%
Water pipe replacement (High demand + Same diameter)				900	1,417		268		535	1,447	3,879	3,906	2,345	14,697	17%
Water pipe replacement (Low demand + Same diameter)		450	548	717			131	1,278	1,087	606	2,102	6,787	3,820	17,526	20%
Water pipe replacement (Low demand + Bigger diameter)			828		393			546	69			350	1,642	3,828	4%
Resurfacing	441		5,508	3,561	238	412	182	47	237					10,626	12%
Total	441	450	8,414	5,978	4,077	4,293	4,266	5,404	5,720	6,542	11,258	14,908	14,399	86,149	0%

Table 8-49: *Intervention actions distribution among the corridors (Scenario 5)*

Corridor #/Action	Reconstruction	Partial Coordination - Road and sewer (High demand + Bigger diameter)	Partial Coordination - Road and sewer (Low demand + Same diameter)	Partial Coordination - Road and sewer (Low demand + Bigger diameter)	Water pipe replacement (High demand + Same diameter)	Water pipe replacement (Low demand + Same diameter)	Water pipe replacement (Low demand + Bigger diameter)	Resurfacing	# of Interventions
1		1							1
101					2			1	3
102	1					2			3
103		2				1		2	5
104	1				2				3
106			2					1	3
107				2				1	3
108	1					2			3
109	1					2			3
110				2		1		2	5
111	1					2			3
112	1					2			3
113				1	1				2
115				1	1				2
116				2	2				4
117				2				1	3
118		2						1	3
120				1					1
121				1					1
123				1					1
124				1					1
125				1	1				2
126				2					2
127		2					1		3
128				1					1
129				1					1
13						2			2
130				1					1
131				1	1				2
133				1			1		2
134				1			1		2
135				2				1	3
136		1							1
137				1		1			2
138		1				1			2

Corridor #/Action	Reconstruction	Partial Coordination - Road and sewer (High demand + Bigger diameter)	Partial Coordination - Road and sewer (Low demand + Same diameter)	Partial Coordination - Road and sewer (Low demand + Bigger diameter)	Water pipe replacement (High demand + Same diameter)	Water pipe replacement (Low demand + Same diameter)	Water pipe replacement (Low demand + Bigger diameter)	Resurfacing	# of Interventions
139		1				1			2
140		1				1			2
142		1				1			2
143				1	1				2
147			2					1	3
148		1				1			2
149				1					1
150				1		1			2
153		1							1
154			1				1	1	3
158		1							1
159				1					1
162				2					2
164				1					1
167				1		1			2
168		1							1
169				1					1
171						2		1	3
174				1					1
176						2		1	3
177						2		1	3
179						2		1	3
185				1					1
186		1							1
188				1					1
189				1					1
190		2				1		2	5
194				1					1
197				2			2		4
199				1	1				2
20						2			2
201		1							1
205				2					2
206				3				1	4
207				1	1				2
21					4				4
210				2					2

Corridor #/Action	Reconstruction	Partial Coordination - Road and sewer (High demand + Bigger diameter)	Partial Coordination - Road and sewer (Low demand + Same diameter)	Partial Coordination - Road and sewer (Low demand + Bigger diameter)	Water pipe replacement (High demand + Same diameter)	Water pipe replacement (Low demand + Same diameter)	Water pipe replacement (Low demand + Bigger diameter)	Resurfacing	# of Interventions
214				2					2
215		1							1
216		1							1
221		2							2
222				2					2
226		1							1
228					1				1
230			1			1			2
232				1					1
241				1					1
243			1		1				2
244						2	1		3
245			1	1	1				3
255					1				1
256				1					1
258					2				2
259						1	1		2
262							1		1
265		1							1
27		2							2
32						1	1		2
33						2	1		3
34			1						1
37				1					1
40						2		1	3
45		4						1	5
46			1		1				2
47					3			1	4
49				1					1
5						3		1	4
52	1				2				3
55				1					1
61				1					1
64		1				1			2
68						5			5
69					3			2	5
70						2			2

Corridor #/Action	Reconstruction	Partial Coordination - Road and sewer (High demand + Bigger diameter)	Partial Coordination - Road and sewer (Low demand + Same diameter)	Partial Coordination - Road and sewer (Low demand + Bigger diameter)	Water pipe replacement (High demand + Same diameter)	Water pipe replacement (Low demand + Same diameter)	Water pipe replacement (Low demand + Bigger diameter)	Resurfacing	# of Interventions
75		1				1			2
76	1				2				3
77		1				1			2
78				1					1
81						2		1	3
83		1					1		2
84		1				1			2
86	2				4				6
88		2						1	3
89				1					1
90				2	1				3
91				1			1		2
93		1							1
94				1					1
95		2				2			4
96				1					1
# of Interventions	10	42	10	70	39	60	13	27	271

Table 8-50: *Intervention actions distribution across the planning horizon (Scenario 5)*

Corridor #/Period	12	14	15	16	17	18	19	20	21	22	23	24	25	# of Interventions
1										1				1
101					1							2		3
102			1									2		3
103			1				1					1	2	5
104			1									2		3
106			1						1				1	3
107			1									1	1	3
108			1									2		3
109			1									2		3
110			1				1					1	2	5
111			1									2		3
112				1								2		3
113								1					1	2
115						1					1			2
116					1	1					2			4
117			1						1				1	3
118			1						1				1	3
120											1			1
121										1				1
123												1		1
124											1			1
125								1					1	2
126										1	1			2
127								1					2	3
128											1			1
129											1			1
13			1										1	2
130													1	1
131								1					1	2
133								1					1	2
134								1					1	2
135			1								1		1	3
136											1			1
137						1					1			2
138						1						1		2
139							1					1		2
140						1					1			2
142					1					1				2
143					1								1	2
147			1							1			1	3
148							1						1	2
149											1			1
150					1					1				2
153													1	1
154						1							2	3
158											1			1
159												1		1
162									1				1	2
164											1			1
167							1					1		2
168												1		1
169									1					1
171				1							1		1	3
174													1	1
176				1								2		3
177				1								2		3
179						1						2		3
185										1				1
186										1				1
188											1			1
189											1			1
190			1				1						3	5
194											1			1
197							1	1				1	1	4
199						1					1			2
20				1							1			2

Corridor #/Period	12	14	15	16	17	18	19	20	21	22	23	24	25	# of Interventions
201													1	1
205											1		1	2
206			1							1	1		1	4
207								1					1	2
21				1	1						2			4
210												1	1	2
214									1	1				2
215									1					1
216									1					1
221											1	1		2
222									1	1				2
226										1				1
228									1					1
230							1					1		2
232												1		1
241										1				1
243							1					1		2
244			1					1					1	3
245							1					1	1	3
255												1		1
256													1	1
258					1							1		2
259					1							1		2
262									1					1
265													1	1
27									1		1			2
32								1					1	2
33			1					1					1	3
34													1	1
37											1			1
40				1					2					3
45	1								1	1	1	1		5
46					1					1				2
47			1				1			1		1		4
49										1				1
5			1				1		1			1		4
52					1							2		3
55													1	1
61										1				1
64							1					1		2
68		1	1					1					2	5
69				1				1	1				2	5
70		1						1						2
75						1					1			2
76				1									2	3
77								1					1	2
78										1				1
81									1				2	3
83								1					1	2
84								1					1	2
86			1	1									4	6
88			1						1				1	3
89											1			1
90								1				1	1	3
91							1					1		2
93										1				1
94									1					1
95						1	1					2		4
96									1					1
# of Interventions	1	2	23	10	10	10	15	18	21	20	31	49	61	271

8.4.6 *Scenario 6 (Partially-coordinated – roads and water + conventional sewer)*

Table 8-51: *Schedule of intervention actions (number) and distribution across the planning horizon (Scenario 6)*

Action/Period	14	15	16	17	18	19	20	21	22	23	24	25	Total	Distribution
Sewer pipelining (High demand + Same diameter)	1							1		1		14	17	5%
Sewer pipelining (Low demand + Same diameter)	1	1							2	2	6	8	20	6%
Reconstruction	1	8	9	4	9	7	13						51	16%
Partial Coordination - Road and water (High demand + Same diameter)				1									1	0%
Partial Coordination - Road and water (Low demand + Bigger diameter)				1				1				2	4	1%
Sewer pipe replacement (High demand + Bigger diameter)		2						2	6	4	12	35	61	19%
Sewer pipe replacement (Low demand + Same diameter)								4	5	12	32	78	131	41%
Resurfacing		6	9	2	3	3		8					31	10%
Total	3	17	18	8	12	10	13	16	13	19	50	137	316	100%

Table 8-52: *Intervention actions space consumption (m^2) across the planning horizon (Scenario 6)*

Action/Period	14	15	16	17	18	19	20	21	22	23	24	25	Total	Distribution
Sewer pipelining (High demand + Same diameter)	376							421		450		3,035	4,282	5%
Sewer pipelining (Low demand + Same diameter)	376	429							456	587	1,953	3,544	7,345	9%
Reconstruction	377	2,154	2,298	1,061	3,262	3,698	4,048						16,898	20%
Partial Coordination - Road and water (High demand + Same diameter)				1,564									1,564	2%
Partial Coordination - Road and water (Low demand + Bigger diameter)				717				69				30	816	1%
Sewer pipe replacement (High demand + Bigger diameter)		640						463	2,101	1,416	2,148	6,336	13,104	15%
Sewer pipe replacement (Low demand + Same diameter)								2,519	1,696	4,125	7,341	14,277	29,958	35%
Resurfacing		4,348	4,130	527	844	524		1,778					12,151	14%
Total	1,129	7,571	6,428	3,869	4,106	4,222	4,048	5,250	4,253	6,578	11,442	27,222	86,118	100%

Table 8-53: *Intervention actions distribution among the corridors (Scenario 6)*

Corridor #/Action	Sewer pipelining (High demand + Same diameter)	Sewer pipelining (Low demand + Same diameter)	Reconstruction	Partial Coordination - Road and water (High demand + Same diameter)	Partial Coordination - Road and water (Low demand + Bigger diameter)	Sewer pipe replacement (High demand + Bigger diameter)	Sewer pipe replacement (Low demand + Same diameter)	Resurfacing	# of interventions
1	2		1						3
101							2	1	3
102			1				2		3
103					1	2		2	5
104			1				2		3
106							3	2	5
107							3	2	5
108			1				2		3
109			1			2			3
110					1		2	2	5
111			1			2			3
112			1			2			3
113			1				2		3
115			1				2		3
116			1				2		3
117							2	1	3
118						2		1	3
120							2	1	3
121							1		1
123							2		2
124							1		1
125			2				4		6
126							1		1
127			1			2			3
128							2	1	3
129							2	1	3
13						2			2
130							1		1
131			1				2		3
133			1				2		3
134			1				2		3
135							3	1	4
136						1			1
137			2				4		6

Corridor #/Action	Sewer pipelining (High demand + Same diameter)	Sewer pipelining (Low demand + Same diameter)	Reconstruction	Partial Coordination - Road and water (High demand + Same diameter)	Partial Coordination - Road and water (Low demand + Bigger diameter)	Sewer pipe replacement (High demand + Bigger diameter)	Sewer pipe replacement (Low demand + Same diameter)	Resurfacing	# of interventions
138			1			2			3
139			1			2			3
140			1			2			3
142			1			2			3
143			1				2		3
147							2	1	3
148			1			2			3
149							1		1
150			1				2		3
153						1			1
154			1				2		3
158						1			1
159							1		1
162							1		1
164							2		2
167							3	1	4
168						1			1
169							1		1
171							3	1	4
174			1				3		4
176		2						1	3
177							2	1	3
179						2		1	3
185							1		1
186						1			1
188							1		1
189							1		1
190						3		2	5
194							1		1
197							1		1
199			1				2		3
20	1				1				2
201						1			1
205			1				2		3
206							1		1
207							1		1

Corridor #/Action	Sewer pipelining (High demand + Same diameter)	Sewer pipelining (Low demand + Same diameter)	Reconstruction	Partial Coordination - Road and water (High demand + Same diameter)	Partial Coordination - Road and water (Low demand + Bigger diameter)	Sewer pipe replacement (High demand + Bigger diameter)	Sewer pipe replacement (Low demand + Same diameter)	Resurfacing	# of interventions
21		2	1	1			1		5
210							2	1	3
214							1		1
215						1			1
216						2			2
221						1			1
222							1		1
226						1			1
228							1		1
230							1		1
232							1		1
241		1					1		2
243		1					1		2
244						2			2
245		1					1		2
255							1		1
256			1				3		4
258			1				2		3
259			1				2		3
262					1				1
265						1			1
27	2		2			2			6
32		1	1				1		3
33		2							2
34		1							1
37							2	1	3
40	2							1	3
45	2		1						3
46		2							2
47							2	1	3
49							1		1
5	2							1	3
52		4	2						6
55							2		2
61		1							1
64	1					1			2

Corridor #/Action	Sewer pipelining (High demand + Same diameter)	Sewer pipelining (Low demand + Same diameter)	Reconstruction	Partial Coordination - Road and water (High demand + Same diameter)	Partial Coordination - Road and water (Low demand + Bigger diameter)	Sewer pipe replacement (High demand + Bigger diameter)	Sewer pipe replacement (Low demand + Same diameter)	Resurfacing	# of interventions
68	3		2			1			6
69		2						1	3
70	2								2
75			1			2			3
76			1				2		3
77			1			2			3
78							1		1
81						1			1
83			1			2			3
84			1			2			3
86			2				4		6
88						2		1	3
89							1		1
90			1				2		3
91			1				2		3
93						1			1
94							2	1	3
95			1			2			3
96							1		1
# of interventions	17	20	51	1	4	61	131	31	316

Table 8-54: *Intervention actions distribution across the planning horizon (Scenario 6)*

Corridor #/Period	14	15	16	17	18	19	20	21	22	23	24	25	# of interventions
1					1							2	3
101					1						2		3
102		1									2		3
103		1				1					1	2	5
104		1									2		3
106			1					1			1	2	5
107				1				1			1	2	5
108		1									2		3
109		1									2		3
110		1				1					1	2	5
111		1									2		3
112			1								2		3
113							1					2	3
115				1								2	3
116			1									2	3
117			1								1	1	3
118			1								1	1	3
120								1				2	3
121											1		1
123										1	1		2
124											1		1
125						1	1					4	6
126										1			1
127							1					2	3
128								1				2	3
129								1				2	3
13		1										1	2
130												1	1
131							1					2	3
133							1					2	3
134							1					2	3
135					1						1	2	4
136											1		1
137			1	1							1	3	6
138				1								2	3
139					1							2	3
140			1									2	3
142			1									2	3
143			1									2	3
147			1									2	3
148						1						2	3
149											1		1
150			1									2	3
153								1					1
154							1					2	3
158												1	1
159								1					1
162											1		1
164											1	1	2
167		1								2	1		4
168										1			1
169												1	1
171		1								1	1	1	4
174							1					3	4
176			1								2		3
177			1								2		3
179					1						2		3
185										1			1
186										1			1

Corridor #/Period	14	15	16	17	18	19	20	21	22	23	24	25	# of interventions
188										1			1
189										1			1
190				1				1		1		2	5
194									1				1
197								1					1
199						1						2	3
20				1								1	2
201									1				1
205						1						2	3
206												1	1
207										1			1
21				1	1							3	5
210								1				2	3
214								1					1
215									1				1
216								1	1				2
221									1				1
222									1				1
226									1				1
228									1				1
230											1		1
232											1		1
241									1	1			2
243										1	1		2
244		1										1	2
245									1	1			2
255								1					1
256						1					1	2	4
258					1							2	3
259					1							2	3
262								1					1
265										1			1
27				1	1							4	6
32							1					2	3
33		1										1	2
34										1			1
37								1				2	3
40			1							1		1	3
45		1										2	3
46	1											1	2
47		1										2	3
49									1				1
5		1										2	3
52					1	1					4		6
55									1	1			2
61												1	1
64								1	1				2
68	1	1										4	6
69			1									2	3
70	1											1	2
75					1							2	3
76			1									2	3
77							1					2	3
78											1		1
81												1	1
83							1					2	3
84							1					2	3
86		1	1									4	6
88			1								1	1	3
89												1	1
90							1					2	3
91						1						2	3

Corridor #/Period	14	15	16	17	18	19	20	21	22	23	24	25	# of interventions
93												1	1
94						1					2		3
95					1							2	3
96											1		1
# of interventions	3	17	18	8	12	10	13	16	13	19	50	137	316

8.4.7 *Scenario 7 (Partially-coordinated – water and sewer + conventional roads)*

Table 8-55: *Schedule of intervention actions (number) and distribution across the planning horizon (Scenario 7)*

Action/Period	14	15	16	17	18	19	20	21	22	23	24	25	Total	Distribution
Reconstruction		8	6	5	7	10	13						49	14%
Resurfacing	1	7	8	2	3	3		16					40	12%
Partial Coordination - Water and sewer (High sewer demand + Same diameter + Low water demand + Same diameter)											2	2	4	1%
Partial Coordination - Water and sewer (High sewer demand + Bigger diameter + Low water demand + Same diameter)	2						5	7	6	7	2	12	41	12%
Partial Coordination - Water and sewer (High sewer demand + Bigger diameter + Low water demand + Bigger diameter)		1	1	1				4	4	7	7	17	42	12%
Partial Coordination - Water and sewer (Low sewer demand + Same diameter + High water demand + Same diameter)										2		1	3	1%
Partial Coordination - Water and sewer (Low sewer demand + Same diameter + High water demand + Bigger diameter)												2	2	1%
Partial Coordination - Water and sewer (Low sewer demand + Same diameter + Low water demand + Same diameter)												3	3	1%
Partial Coordination - Water and sewer (Low sewer demand + Same diameter + Low water demand + Bigger diameter)								2					2	1%
Partial Coordination - Water and sewer (Low sewer demand + Bigger diameter + High water demand + Same diameter)								2	2	1		1	6	2%
Partial Coordination - Water and sewer (Low sewer demand + Bigger diameter + High water demand + Bigger diameter)	1			1	1		2	13	11	9	14	21	73	22%
Partial Coordination - Water and sewer (Low sewer demand + Bigger diameter + Low water demand + Same diameter)							3	5	2	3	6	7	26	8%
Partial Coordination - Water and sewer (Low sewer demand + Bigger diameter + High water demand + Bigger diameter)		1						3	3	6	6	28	47	14%
Total	4	17	15	9	11	13	23	52	28	35	37	94	338	100%

Table 8-56: *Intervention actions space consumption (m^2) across the planning horizon (Scenario 7)*

Action/Period	14	15	16	17	18	19	20	21	22	23	24	25	Total	Distribution
Reconstruction		2,535	1,830	1,786	3,417	3,573	4,390						17,531	20%
Resurfacing	22	3,949	3,819	527	844	848		2,461					12,470	14%
Partial Coordination - Water and sewer (High sewer demand + Same diameter + Low water demand + Same diameter)											467	953	1,420	2%
Partial Coordination - Water and sewer (High sewer demand + Bigger diameter + Low water demand + Same diameter)	757						1,238	909	1,208	1,606	378	1,500	7,595	9%
Partial Coordination - Water and sewer (High sewer demand + Bigger diameter + Low water demand + Bigger diameter)		399	649	68				907	1,386	1,612	1,797	2,796	9,614	11%
Partial Coordination - Water and sewer (Low sewer demand + Same diameter + High water demand + Same diameter)										380		1,590	1,970	2%
Partial Coordination - Water and sewer (Low sewer demand + Same diameter + High water demand + Bigger diameter)												411	411	0%

Action/Period	14	15	16	17	18	19	20	21	22	23	24	25	Total	Distribution
Partial Coordination - Water and sewer (Low sewer demand + Same diameter + Low water demand + Same diameter)												1,339	1,339	2%
Partial Coordination - Water and sewer (Low sewer demand + Same diameter + Low water demand + Bigger diameter)								972					972	1%
Partial Coordination - Water and sewer (Low sewer demand + Bigger diameter + High water demand + Same diameter)								236	265	145		582	1,228	1%
Partial Coordination - Water and sewer (Low sewer demand + Bigger diameter + High water demand + Bigger diameter)	376			1,590	4		494	2,701	2,662	3,002	4,860	4,235	19,924	23%
Partial Coordination - Water and sewer (Low sewer demand + Bigger diameter + Low water demand + Same diameter)							1,102	518	381	679	757	822	4,259	5%
Partial Coordination - Water and sewer (Low sewer demand + Bigger diameter + High water demand + Bigger diameter)		429						1,067	675	931	1,513	5,105	9,720	11%
Total	1,155	7,312	6,298	3,971	4,265	4,421	7,224	9,771	6,577	8,356	9,772	19,333	88,453	100%

Table 8-57: *Intervention actions distribution among the corridors (Scenario 7)*

Corridor #/Action	Reconstruction	Resurfacing	Partial Coordination - Water and sewer (High sewer demand + Same diameter + Low water demand + Same diameter)	Partial Coordination - Water and sewer (High sewer demand + Bigger diameter + Low water demand + Same diameter)	Partial Coordination - Water and sewer (High sewer demand + Bigger diameter + Low water demand + Bigger diameter)	Partial Coordination - Water and sewer (Low sewer demand + Same diameter + High water demand + Same diameter)	Partial Coordination - Water and sewer (Low sewer demand + Same diameter + High water demand + Bigger diameter)	Partial Coordination - Water and sewer (Low sewer demand + Same diameter + Low water demand + Same diameter)	Partial Coordination - Water and sewer (Low sewer demand + Same diameter + Low water demand + Bigger diameter)	Partial Coordination - Water and sewer (Low sewer demand + Bigger diameter + High water demand + Same diameter)	Partial Coordination - Water and sewer (Low sewer demand + Bigger diameter + High water demand + Bigger diameter)	Partial Coordination - Water and sewer (Low sewer demand + Bigger diameter + Low water demand + Same diameter)	Partial Coordination - Water and sewer (Low sewer demand + Bigger diameter + High water demand + Bigger diameter)	# of intervention
1	1			1	1									3
101		1									2			3
102	1							1				2		4
103		2			3									5
104	1										2			3
106		2									3			5
107		2									4			6
108	1											2		3
109	1		1	2										4
110		2										3		5
111	1			1	1									3
112	1			2										3
113											2			2
115	1									2				3
116	1										2			3
117		2										2	1	5
118		2		2	1									5
120		1									2			3
121											2			2

Corridor #/Action	Reconstruction	Resurfacing	Partial Coordination - Water and sewer (High sewer demand + Same diameter + Low water demand + Same diameter)	Partial Coordination - Water and sewer (High sewer demand + Bigger diameter + Low water demand + Same diameter)	Partial Coordination - Water and sewer (High sewer demand + Bigger diameter + Low water demand + Bigger diameter)	Partial Coordination - Water and sewer (Low sewer demand + Same diameter + High water demand + Same diameter)	Partial Coordination - Water and sewer (Low sewer demand + Same diameter + High water demand + Bigger diameter)	Partial Coordination - Water and sewer (Low sewer demand + Same diameter + Low water demand + Same diameter)	Partial Coordination - Water and sewer (Low sewer demand + Same diameter + Low water demand + Bigger diameter)	Partial Coordination - Water and sewer (Low sewer demand + Bigger diameter + High water demand + Same diameter)	Partial Coordination - Water and sewer (Low sewer demand + Bigger diameter + High water demand + Bigger diameter)	Partial Coordination - Water and sewer (Low sewer demand + Bigger diameter + Low water demand + Same diameter)	Partial Coordination - Water and sewer (Low sewer demand + Bigger diameter + High water demand + Bigger diameter)	# of intervention
123													1	1
124											1			1
125	1										2			3
126													2	2
127					1									1
128		1									2			3
129		1											2	3
13		2		4										6
130													1	1
131											1			1
133													1	1
134													2	2
135		1									2			3
136					1									1
137	1											2		3
138	1			2										3
139	1			2										3
140	1			2										3
142	1			2										3
143	1									2				3
147		2									3			5
148	1			1	1									3
149													1	1
150	1											2		3
153					1									1
154	1												2	3
158					1									1
159													1	1
162											1			1
164											1			1
167	2											4		6
168					1									1
169	1										2			3

Corridor #/Action	Reconstruction	Resurfacing	Partial Coordination - Water and sewer (High sewer demand + Same diameter + Low water demand + Same diameter)	Partial Coordination - Water and sewer (High sewer demand + Bigger diameter + Low water demand + Same diameter)	Partial Coordination - Water and sewer (High sewer demand + Bigger diameter + Low water demand + Bigger diameter)	Partial Coordination - Water and sewer (Low sewer demand + Same diameter + High water demand + Same diameter)	Partial Coordination - Water and sewer (Low sewer demand + Same diameter + High water demand + Bigger diameter)	Partial Coordination - Water and sewer (Low sewer demand + Same diameter + Low water demand + Same diameter)	Partial Coordination - Water and sewer (Low sewer demand + Same diameter + Low water demand + Bigger diameter)	Partial Coordination - Water and sewer (Low sewer demand + Bigger diameter + High water demand + Same diameter)	Partial Coordination - Water and sewer (Low sewer demand + Bigger diameter + High water demand + Bigger diameter)	Partial Coordination - Water and sewer (Low sewer demand + Bigger diameter + Low water demand + Same diameter)	Partial Coordination - Water and sewer (Low sewer demand + Bigger diameter + High water demand + Bigger diameter)	# of intervention
171		1						1				2		4
174											1			1
176		2							2				2	6
177		1											2	3
179		1		2										3
185		1									2			3
186		1		2										3
188	1											1	1	3
189	1											1	1	3
190		2		3										5
194													1	1
197	1												3	4
199	1										3			4
20			2		2									4
201					1									1
205	1											2		3
206	2												4	6
207	1										2			3
21						1					1			2
210		1										1	1	3
214													1	1
215	1				3									4
216	1			1	2									4
221					1									1
222											2			2
226					2									2
228											1			1
230													1	1
232											1			1
241	1												3	4
243											2			2
244			1		1									2
245											1			1

Corridor #/Action	Reconstruction	Resurfacing	Partial Coordination - Water and sewer (High sewer demand + Same diameter + Low water demand + Same diameter)	Partial Coordination - Water and sewer (High sewer demand + Bigger diameter + Low water demand + Same diameter)	Partial Coordination - Water and sewer (High sewer demand + Bigger diameter + Low water demand + Bigger diameter)	Partial Coordination - Water and sewer (Low sewer demand + Same diameter + High water demand + Same diameter)	Partial Coordination - Water and sewer (Low sewer demand + Same diameter + High water demand + Bigger diameter)	Partial Coordination - Water and sewer (Low sewer demand + Same diameter + Low water demand + Same diameter)	Partial Coordination - Water and sewer (Low sewer demand + Same diameter + Low water demand + Bigger diameter)	Partial Coordination - Water and sewer (Low sewer demand + Bigger diameter + High water demand + Same diameter)	Partial Coordination - Water and sewer (Low sewer demand + Bigger diameter + High water demand + Bigger diameter)	Partial Coordination - Water and sewer (Low sewer demand + Bigger diameter + Low water demand + Same diameter)	Partial Coordination - Water and sewer (Low sewer demand + Bigger diameter + High water demand + Bigger diameter)	# of intervention
255											1			1
256	1											2	1	4
258	1									2				3
259	2												4	6
262					1									1
265					1									1
27	1			2										3
32													1	1
33								1					1	2
34	1						2							3
37		1											2	3
40		1			2									3
45	1			2										3
46						1					1			2
47		2				1					4			7
49											1			1
5		1			2									3
52	1										2			3
55	1												2	3
61	1										3			4
64					2									2
68				2										2
69											1			1
70				2										2
75	1			1	1									3
76	1										2			3
77					1									1
78											1			1
81		1			2									3
83					1									1
84					1									1
86	1										2			3
88		2		3										5

Corridor #/Action	Reconstruction	Resurfacing	Partial Coordination - Water and sewer (High sewer demand + Same diameter + Low water demand + Same diameter)	Partial Coordination - Water and sewer (High sewer demand + Bigger diameter + Low water demand + Same diameter)	Partial Coordination - Water and sewer (High sewer demand + Bigger diameter + Low water demand + Bigger diameter)	Partial Coordination - Water and sewer (Low sewer demand + Same diameter + High water demand + Same diameter)	Partial Coordination - Water and sewer (Low sewer demand + Same diameter + High water demand + Bigger diameter)	Partial Coordination - Water and sewer (Low sewer demand + Same diameter + Low water demand + Same diameter)	Partial Coordination - Water and sewer (Low sewer demand + Same diameter + Low water demand + Bigger diameter)	Partial Coordination - Water and sewer (Low sewer demand + Bigger diameter + High water demand + Same diameter)	Partial Coordination - Water and sewer (Low sewer demand + Bigger diameter + High water demand + Bigger diameter)	Partial Coordination - Water and sewer (Low sewer demand + Bigger diameter + Low water demand + Same diameter)	Partial Coordination - Water and sewer (Low sewer demand + Bigger diameter + High water demand + Bigger diameter)	# of intervention
89											1			1
90											1			1
91	1												2	3
93	1				2									3
94		1									2			3
95	1				2									3
96											1			1
# of intervention	49	40	4	41	42	3	2	3	2	6	73	26	47	338

Table 8-58: *Intervention actions distribution across the planning horizon (Scenario 7)*

Corridor #/Period	14	15	16	17	18	19	20	21	22	23	24	25	# of intervention
1						1						2	3
101					1				2				3
102		1					1	1				1	4
103		1						1				3	5
104		1					1	1					3
106			1				1	1				2	5
107				1				2	1			2	6
108		1					1	1					3
109		1					1	1				1	4
110		1						1		1		2	5
111		1					1	1					3
112		1					1	1					3
113										1		1	2
115				1					2				3
116			1					2					3
117			1					2				2	5
118			1					2				2	5
120								1				2	3
121								1		1			2
123								1					1
124												1	1
125						1					2		3
126								1	1				2
127										1			1
128								1				2	3
129								1				2	3
13		1						1		1		3	6
130									1				1
131											1		1
133												1	1
134										1	1		2
135					1				2				3
136								1					1
137				1					2				3
138				1					2				3
139					1					2			3
140			1					1	1				3
142			1					2					3
143			1					2					3
147			1					2				2	5
148						1					2		3
149												1	1
150			1					2					3
153								1					1
154							1					2	3
158										1			1
159											1		1
162									1				1
164								1					1
167					1	1				2	2		6
168									1				1
169							1					2	3
171		1					1					2	4
174											1		1
176		1	1					2				2	6
177			1					1				1	3
179					1				2				3
185						1				1	1		3
186						1				1	1		3

Corridor #/Period	14	15	16	17	18	19	20	21	22	23	24	25	# of intervention
188							1					2	3
189							1					2	3
190				1				2				2	5
194									1				1
197						1					2	1	4
199						1					2	1	4
20			1	1							1	1	4
201									1				1
205						1					2		3
206						1	1					4	6
207							1					2	3
21				1								1	2
210								1				2	3
214										1			1
215							1	1				2	4
216							1			1		2	4
221									1				1
222								1	1				2
226										1	1		2
228									1				1
230												1	1
232												1	1
241							1			1		2	4
243										1	1		2
244		1									1		2
245											1		1
255										1			1
256						1				1	2		4
258				1						1		1	3
259				1	1					2		2	6
262										1			1
265											1		1
27					1					2			3
32												1	1
33		1										1	2
34							1					2	3
37								1				2	3
40			1							1		1	3
45		1					2						3
46	1									1			2
47	1	1			1					1	3		7
49									1				1
5		1										2	3
52					1					2			3
55							1					2	3
61							1	1				2	4
64									1			1	2
68	1											1	2
69												1	1
70	1											1	2
75					1					1	1		3
76			1					1	1				3
77										1			1
78								1					1
81								1				2	3
83												1	1
84											1		1
86		1						2					3
88			1					1	1			2	5
89											1		1
90										1			1
91						1					2		3

Corridor #/Period	14	15	16	17	18	19	20	21	22	23	24	25	# of intervention
93							1					2	3
94						1				1	1		3
95					1						2		3
96									1				1
# of intervention	4	17	15	9	11	13	23	52	28	35	37	94	338

8.4.8 *Scenario 8 (Fully-coordinated - roads, water, and sewer)*

Table 8-59: *Schedule of intervention actions (number) and distribution across the planning horizon (Scenario 8)*

Action/Period	12	14	15	16	17	18	19	20	21	22	23	24	25	Total	Distribution
Reconstruction			1				1							2	1%
Resurfacing	1		1	14										16	1%
Full Coordination - Roads, water, and sewer (Sewer high demand + Bigger diameter + Water low demand + Same diameter)			2	1	1		2	2		2		2	7	19	1%
Full Coordination - Roads, water, and sewer (Sewer high demand + Bigger diameter + Water low demand + Bigger diameter)		1	2	3	1	3	5	4	3	7	4	3	7	43	1%
Full Coordination - Roads, water, and sewer (Sewer low demand + Same diameter + Water high demand + Same diameter)													1	1	1%
Full Coordination - Roads, water, and sewer (Sewer low demand + Same diameter + Water high demand + Bigger diameter)												2	2	4	1%
Full Coordination - Roads, water, and sewer (Sewer low demand + Same diameter + Water low demand + Same diameter)													1	1	1%
Full Coordination - Roads, water, and sewer (Sewer low demand + Bigger diameter + Water high demand + Bigger diameter)			3	3	4	5	1	4	7	9	10	3	5	54	1%
Full Coordination - Roads, water, and sewer (Sewer low demand + Bigger diameter + Water low demand + Same diameter)				2		1	1		1				1	6	1%
Full Coordination - Roads, water, and sewer (Sewer low demand + Bigger diameter + Water low demand + Bigger diameter)			1	1	4		3	5	5	5	2	7	7	40	1%
Total	1	1	10	24	10	9	13	15	16	23	16	17	31	186	1%

Table 8-60: *Intervention actions space consumption (m^2) across the planning horizon (Scenario 8)*

Action/Period	12	14	15	16	17	18	19	20	21	22	23	24	25	Total	Distribution
Reconstruction			86				361							447	1%
Resurfacing	441		241	4,217										4,899	8%
Full Coordination - Roads, water, and sewer (Sewer high demand + Bigger diameter + Water low demand + Same diameter)			757	380	376		606	284		105		217	1,952	4,677	8%
Full Coordination - Roads, water, and sewer (Sewer high demand + Bigger diameter + Water low demand + Bigger diameter)		24	1,092	1,272	562	1,016	1,569	1,054	804	1,683	808	841	2,169	12,893	21%
Full Coordination - Roads, water, and sewer (Sewer low demand + Same diameter + Water high demand + Same diameter)													1,504	1,504	2%

Action/Period	12	14	15	16	17	18	19	20	21	22	23	24	25	Total	Distribution
Full Coordination - Roads, water, and sewer (Sewer low demand + Same diameter + Water high demand + Bigger diameter)												64	258	322	1%
Full Coordination - Roads, water, and sewer (Sewer low demand + Same diameter + Water low demand + Same diameter)													429	429	1%
Full Coordination - Roads, water, and sewer (Sewer low demand + Bigger diameter + Water high demand + Bigger diameter)			2,994	483	1,748	2,716	236	1,205	2,282	2,105	3,336	2,263	1,513	20,881	34%
Full Coordination - Roads, water, and sewer (Sewer low demand + Bigger diameter + Water low demand + Same diameter)				1,140		381	693		76				304	2,594	4%
Full Coordination - Roads, water, and sewer (Sewer low demand + Bigger diameter + Water low demand + Bigger diameter)			429	238	2,487		620	1,835	1,389	828	715	1,819	1,995	12,355	20%
Total	441	24	5,599	7,730	5,173	4,113	4,085	4,378	4,551	4,721	4,859	5,204	10,124	61,001	100%

Table 8-61: *Intervention actions distribution among the corridors (Scenario 8)*

Corridor #/Action	Reconstruction	Resurfacing	Full Coordination - Roads, water, and sewer (Sewer high demand + Bigger diameter + Water low demand + Same diameter)	Full Coordination - Roads, water, and sewer (Sewer high demand + Bigger diameter + Water low demand + Bigger diameter)	Full Coordination - Roads, water, and sewer (Sewer low demand + Same diameter + Water high demand + Same diameter)	Full Coordination - Roads, water, and sewer (Sewer low demand + Same diameter + Water high demand + Bigger diameter)	Full Coordination - Roads, water, and sewer (Sewer low demand + Same diameter + Water low demand + Same diameter)	Full Coordination - Roads, water, and sewer (Sewer low demand + Bigger diameter + Water high demand + Bigger diameter)	Full Coordination - Roads, water, and sewer (Sewer low demand + Bigger diameter + Water low demand + Same diameter)	Full Coordination - Roads, water, and sewer (Sewer low demand + Bigger diameter + Water low demand + Bigger diameter)	# of interventions
1				1							1
101								1			1
102										1	1
103		1		2							3
104								1			1
106		1						2			3
107		1						2			3
108									1		1
109			1								1
110		1							2		3
111				1							1
112				1							1
113								1			1
115								1			1
116								1			1
117		1								2	3

Corridor #/Action	Reconstruction	Resurfacing	Full Coordination - Roads, water, and sewer (Sewer high demand + Bigger diameter + Water low demand + Same diameter)	Full Coordination - Roads, water, and sewer (Sewer high demand + Bigger diameter + Water low demand + Bigger diameter)	Full Coordination - Roads, water, and sewer (Sewer low demand + Same diameter + Water high demand + Same diameter)	Full Coordination - Roads, water, and sewer (Sewer low demand + Same diameter + Water high demand + Bigger diameter)	Full Coordination - Roads, water, and sewer (Sewer low demand + Same diameter + Water low demand + Same diameter)	Full Coordination - Roads, water, and sewer (Sewer low demand + Bigger diameter + Water high demand + Bigger diameter)	Full Coordination - Roads, water, and sewer (Sewer low demand + Bigger diameter + Water low demand + Same diameter)	Full Coordination - Roads, water, and sewer (Sewer low demand + Bigger diameter + Water low demand + Bigger diameter)	# of interventions
118		1		2							3
120								1			1
121								1			1
123										1	1
124								1			1
125								1			1
126										2	2
127				1							1
128								2			2
129										2	2
13		1	2								3
130										1	1
131								1			1
133										1	1
134										1	1
135		1						2			3
136				1							1
137									1		1
138				1							1
139			1								1
140				1							1
142			1								1
143								1			1
147		1						2			3
148				1							1
149										1	1
150										1	1
153				1							1
154										2	2
158				1							1
159										1	1
162								1			1
164								1			1
167									1		1
168				1							1

Corridor #/Action	Reconstruction	Resurfacing	Full Coordination - Roads, water, and sewer (Sewer high demand + Bigger diameter + Water low demand + Same diameter)	Full Coordination - Roads, water, and sewer (Sewer high demand + Bigger diameter + Water low demand + Bigger diameter)	Full Coordination - Roads, water, and sewer (Sewer low demand + Same diameter + Water high demand + Same diameter)	Full Coordination - Roads, water, and sewer (Sewer low demand + Same diameter + Water high demand + Bigger diameter)	Full Coordination - Roads, water, and sewer (Sewer low demand + Same diameter + Water low demand + Same diameter)	Full Coordination - Roads, water, and sewer (Sewer low demand + Bigger diameter + Water high demand + Bigger diameter)	Full Coordination - Roads, water, and sewer (Sewer low demand + Bigger diameter + Water low demand + Same diameter)	Full Coordination - Roads, water, and sewer (Sewer low demand + Bigger diameter + Water low demand + Bigger diameter)	# of interventions
169								1			1
171									1		1
174								2			2
176										1	1
177										1	1
179			1								1
185								2			2
186			1								1
188										1	1
189										1	1
190		1	2								3
194										2	2
197										1	1
199								1			1
20			1	1							2
201				1							1
205										1	1
206		1								2	3
207								1			1
21	1				1	2		1			5
210										1	1
214										2	2
215				1							1
216				1							1
221				2							2
222								2			2
226				1							1
228								1			1
230										1	1
232								1			1
241										1	1
243								1			1
244			2	2							4
245								1			1
255								1			1

Corridor #/Action	Reconstruction	Resurfacing	Full Coordination - Roads, water, and sewer (Sewer high demand + Bigger diameter + Water low demand + Same diameter)	Full Coordination - Roads, water, and sewer (Sewer high demand + Bigger diameter + Water low demand + Bigger diameter)	Full Coordination - Roads, water, and sewer (Sewer low demand + Same diameter + Water high demand + Same diameter)	Full Coordination - Roads, water, and sewer (Sewer low demand + Same diameter + Water high demand + Bigger diameter)	Full Coordination - Roads, water, and sewer (Sewer low demand + Same diameter + Water low demand + Same diameter)	Full Coordination - Roads, water, and sewer (Sewer low demand + Bigger diameter + Water high demand + Bigger diameter)	Full Coordination - Roads, water, and sewer (Sewer low demand + Bigger diameter + Water low demand + Same diameter)	Full Coordination - Roads, water, and sewer (Sewer low demand + Bigger diameter + Water low demand + Bigger diameter)	# of interventions
256										2	2
258								2			2
259										1	1
262				2							2
265				2							2
27				2							2
32										2	2
33							1			1	2
34								1			1
37										1	1
40				1							1
45		2	3								5
46	1							1			2
47								1			1
49								1			1
5				1							1
52								1			1
55										1	1
61								1			1
64				1							1
68			1								1
69		1				2					3
70			1								1
75				2							2
76								1			1
77				2							2
78								1			1
81				1							1
83		1		2							3
84				1							1
86								2			2
88		1	2								3
89								1			1
90								1			1
91										1	1

Corridor #/Action	Reconstruction	Resurfacing	Full Coordination - Roads, water, and sewer (Sewer high demand + Bigger diameter + Water low demand + Same diameter)	Full Coordination - Roads, water, and sewer (Sewer high demand + Bigger diameter + Water low demand + Bigger diameter)	Full Coordination - Roads, water, and sewer (Sewer low demand + Same diameter + Water high demand + Same diameter)	Full Coordination - Roads, water, and sewer (Sewer low demand + Same diameter + Water high demand + Bigger diameter)	Full Coordination - Roads, water, and sewer (Sewer low demand + Same diameter + Water low demand + Same diameter)	Full Coordination - Roads, water, and sewer (Sewer low demand + Bigger diameter + Water high demand + Bigger diameter)	Full Coordination - Roads, water, and sewer (Sewer low demand + Bigger diameter + Water low demand + Same diameter)	Full Coordination - Roads, water, and sewer (Sewer low demand + Bigger diameter + Water low demand + Bigger diameter)	# of interventions
93				1							1
94								1			1
95				1							1
96								1			1
# of interventions	2	16	19	43	1	4	1	54	6	40	186

Table 8-62: *Intervention actions distribution across the planning horizon (Scenario 8)*

Corrido #/Period	12	14	15	16	17	18	19	20	21	22	23	24	25	# of interventions
1										1				1
101						1								1
102				1										1
103				1					1				1	3
104				1										1
106				1						1			1	3
107				1							1		1	3
108				1										1
109				1										1
110				1					1				1	3
111				1										1
112				1										1
113								1						1
115						1								1
116						1								1
117				1						1			1	3
118				1						1			1	3
120										1				1
121									1					1
123												1		1
124										1				1
125							1							1
126										1		1		2
127								1						1
128									1		1			2
129									1	1				2
13			1					1				1		3
130												1		1
131								1						1
133								1						1
134								1						1
135				1						1			1	3
136										1				1
137						1								1
138						1								1
139							1							1
140						1								1
142					1									1
143					1									1
147				1						1			1	3
148							1							1
149									1					1
150					1									1
153											1			1
154							1	1						2
158										1				1
159								1						1
162										1				1
164										1				1
167							1							1
168										1				1

Corrido #/Period	12	14	15	16	17	18	19	20	21	22	23	24	25	# of interventions
169									1					1
171				1										1
174									1		1			2
176					1									1
177					1									1
179							1							1
185								1	1					2
186								1						1
188											1			1
189									1					1
190				1						1			1	3
194									1	1				2
197							1							1
199						1								1
20			1										1	2
201													1	1
205										1				1
206				1									2	3
207											1			1
21			2									1	2	5
210													1	1
214												1	1	2
215													1	1
216													1	1
221							1			1				2
222										1	1			2
226												1		1
228											1			1
230												1		1
232												1		1
241													1	1
243												1		1
244		1	1									1	1	4
245											1			1
255												1		1
256											1	1		2
258					1	1								2
259					1									1
262											1	1		2
265												1	1	2
27									1	1				2
32								1				1		2
33			1										1	2
34													1	1
37													1	1
40					1									1
45	1			1									3	5
46				1			1							2
47			1											1
49											1			1
5				1										1
52					1									1
55									1					1

Corrido #/Period	12	14	15	16	17	18	19	20	21	22	23	24	25	# of interventions
61									1					1
64							1							1
68			1											1
69				1								1	1	3
70			1											1
75						1	1							2
76					1									1
77								1			1			2
78									1					1
81								1						1
83				1					1				1	3
84								1						1
86			1	1										2
88				1						1			1	3
89											1			1
90								1						1
91							1							1
93											1			1
94											1			1
95							1							1
96										1				1
# of interventions	1	1	10	24	10	9	13	15	16	23	16	17	31	186

8.5 Appendix E: REMSOFT Code

This section displays the code used for both the multi-dimensional and optimization models. It is worth noting that the code varies from one running scenario to another as discussed in the town of Kindersley results section. Thus, this code is the general one that includes all the scenarios (i.e. conventional, partial and full coordination). The differences among the scenarios are in the intervention actions, yields, transitions, outputs, and optimize sections such that, specific actions are considered in each scenario (i.e. full coordination intervention action is not considered in the roads' conventional optimization scenario, etc.).

8.5.1 *Landscape*

```
;-------------------------------------------
; LANDSCAPE Section
; File created on Nov 15 2018 at 8:07:39 am
; Interpreter (Wk32.exe) version       7.4.0
; Editor version (Wke32.exe)          7.4.0
; Lp Report writer (Lp2wk.exe) version 7.4.0
;-------------------------------------------
*THEME {1}
 Gravel
 Road
*AGGREGATE ROADS
 gravel road

*THEME {2}
 Strong
 Weak
```

*THEME {3}

vhigh

High

Light

Medium

*AGGREGATE local

light medium

*AGGREGATE Collector

High vhigh

*THEME {4}

None

CS

MS

PA

RS

RC

Linersewer

linerwater

REPLACESEWER

replacewater

*THEME {5}

Sanitary

Storm

*AGGREGATE SEWER

SANITARY

STORM

*THEME {6}

Ac

Conc

Pvc

Vct

unknown

CSP

VT

*AGGREGATE CONCRETE

CONC AC CSP VCT VT unknown

*AGGREGATE PLASTIC

PVC

*THEME {7}

S10

S12

S15

S18

S21

S24

S30

S6

S8

*AGGREGATE small

s6 s8 s10

*AGGREGATE moyen

s12 s15 s18

*AGGREGATE large

s21 s24 s30

*THEME {8}

No

RDWR

RDSR

SRWR

RWS

*THEME {9}

Wm

*THEME {10}

Ac

Ci

Plastic

Pvc

Steel

Uci

*AGGREGATE IRON

CI UCI Steel

*AGGREGATE PLASTIC2

PVC PLASTIC

*AGGREGATE CONCRETE

AC

*THEME {11}

S12

S16

S6

S8

*AGGREGATE small

s6 s8

*AGGREGATE moyen

s12 s16

*THEME {12}

Non

RWS

*THEME {13}

FOR x := -150 to 150

x

ENDFOR

*THEME {14}

FOR x := -150 to 150

x

ENDFOR

*THEME {15}

15

*THEME {16}

17

*THEME {17}

FOR x := 0 to 265

x

ENDFOR

*THEME {18}

High

Low

Medium

*AGGREGATE LOWDEMANDSEWER

LOW MEDIUM

*THEME {19}

 High

 Low

 Medium

*AGGREGATE LOWDEMANDWATER

 LOW MEDIUM

*THEME {20}

FOR x := -150 to 150

x

ENDFOR

*THEME {21}

FOR x := -150 to 150

x

ENDFOR

8.5.2 *Area*

```
;-------------------------------------------
; AREAS Section
; File created on Nov 19 2018 at 1:58:09 pm
; Interpreter (Wk32.exe) version       7.4.0
; Editor version (Wke32.exe)           7.4.0
; Lp Report writer (Lp2wk.exe) version 7.4.0
;-------------------------------------------
; Area field name   = AREA
; Area divisor      = 1
; Total area found  = 52,966
; Age field name    = AGE
; Age divisor       = 1
; Minimum age found = 1
```

; Maximum age found = 25

; Total number of polygons = 125
; Total area = 52,966
; Polygons <= 0.0000001 0 (0.0%) Area = 0 (0.0%)
; Polygons <= 0.000001 0 (0.0%) Area = 0 (0.0%)
; Polygons <= 0.00001 0 (0.0%) Area = 0 (0.0%)
; Polygons <= 0.0001 0 (0.0%) Area = 0 (0.0%)
; Polygons <= 0.001 0 (0.0%) Area = 0 (0.0%)
; Polygons <= 0.01 0 (0.0%) Area = 0 (0.0%)
; Polygons <= 0.1 0 (0.0%) Area = 0 (0.0%)
; Polygons <= 1 0 (0.0%) Area = 0 (0.0%)

*A GRAVEL WEAK LIGHT NONE SANITARY AC S8 NO WM PVC S6 NON 26 27 15 17 244 HIGH MEDIUM 16 17 18 399 ; 1 polygons
*A GRAVEL WEAK LIGHT NONE SANITARY CONC S8 NO WM AC S6 NON 35 37 15 17 255 LOW HIGH 25 27 18 727 ; 1 polygons
*A GRAVEL WEAK LIGHT NONE SANITARY CONC S8 NO WM PVC S6 NON 35 8 15 17 258 MEDIUM HIGH 25 2 18 727 ; 1 polygons
*A GRAVEL WEAK LIGHT NONE SANITARY PVC S10 NO WM PVC S12 NON 26 21 15 17 230 LOW MEDIUM 16 11 18 273 ; 1 polygons
*A GRAVEL WEAK LIGHT NONE SANITARY PVC S10 NO WM PVC S12 NON 26 21 15 17 232 LOW HIGH 16 11 18 709 ; 1 polygons
*A GRAVEL WEAK LIGHT NONE SANITARY PVC S10 NO WM PVC S16 NON 26 25 15 17 265 HIGH MEDIUM 16 15 18 709 ; 1 polygons
*A GRAVEL WEAK LIGHT NONE SANITARY PVC S8 NO WM AC S6 NON 26 32 15 17 241 MEDIUM MEDIUM 16 22 18 397 ; 1 polygons
*A GRAVEL WEAK LIGHT NONE SANITARY PVC S8 NO WM AC S6 NON 27 42 15 17 34 LOW HIGH 1 32 18 411 ; 1 polygons
*A GRAVEL WEAK LIGHT NONE SANITARY PVC S8 NO WM AC S6 NON 6 37 15 17 32 LOW MEDIUM 4 27 18 546 ; 1 polygons
*A GRAVEL WEAK LIGHT NONE SANITARY PVC S8 NO WM PVC S6 NON 12 27 15 17 20 HIGH LOW 17 17 18 717 ; 1 polygons
*A GRAVEL WEAK LIGHT NONE SANITARY PVC S8 NO WM PVC S6 NON 12 50 15 17 21 LOW HIGH 2 40 18 1,590 ; 1 polygons
*A GRAVEL WEAK LIGHT NONE SANITARY PVC S8 NO WM PVC S6 NON 26 27 15 17 243 LOW HIGH 16 17 18 827 ; 1 polygons
*A GRAVEL WEAK LIGHT NONE SANITARY PVC S8 NO WM PVC S6 NON 26 27 15 17 245 LOW HIGH 16 17 18 727 ; 1 polygons
*A GRAVEL WEAK LIGHT NONE SANITARY PVC S8 NO WM PVC S6 NON 35 8 15 17 256 MEDIUM MEDIUM 25 2 18 546 ; 1 polygons
*A GRAVEL WEAK LIGHT NONE SANITARY PVC S8 NO WM PVC S6 NON 6 27 15 17 33 LOW MEDIUM 4 17 18 429 ; 1 polygons
*A GRAVEL WEAK LIGHT NONE SANITARY VCT S8 NO WM AC S6 NON 40 40 15 17 226 HIGH LOW 30 30 18 211 ; 1 polygons

*A GRAVEL WEAK LIGHT NONE SANITARY VCT S8 NO WM AC S6 NON 42 32 15 17 214 MEDIUM LOW 32 22 18 400 ; 1 polygons
*A GRAVEL WEAK LIGHT NONE SANITARY VCT S8 NO WM PLASTIC S6 NON 42 26 15 17 216 HIGH MEDIUM 32 16 18 727 ; 1 polygons
*A GRAVEL WEAK LIGHT NONE SANITARY VCT S8 NO WM PVC S6 NON 35 27 15 17 259 LOW MEDIUM 25 17 18 393 ; 1 polygons
*A ROAD STRONG HIGH NONE STORM CONC S18 NO WM PVC S8 NON 46 28 15 17 167 MEDIUM LOW 36 18 9 693 ; 1 polygons
*A ROAD STRONG HIGH NONE STORM CONC S18 NO WM UCI S6 NON 44 50 15 17 120 LOW HIGH 34 40 1 235 ; 1 polygons
*A ROAD STRONG HIGH NONE STORM CONC S24 NO WM CI S6 NON 44 57 15 17 81 HIGH LOW 34 47 3 237 ; 1 polygons
*A ROAD STRONG HIGH NONE STORM CONC S8 NO WM AC S6 NON 44 45 15 17 159 MEDIUM MEDIUM 34 35 9 1,012 ; 1 polygons
*A ROAD STRONG HIGH NONE STORM CONC S8 NO WM PVC S16 NON 44 26 15 17 199 MEDIUM HIGH 34 16 9 1,648 ; 1 polygons
*A ROAD STRONG LIGHT NONE SANITARY PVC S8 NO WM AC S6 NON 7 36 15 17 40 HIGH MEDIUM 3 26 5 562 ; 1 polygons
*A ROAD STRONG LIGHT NONE SANITARY PVC S8 NO WM PVC S6 NON 27 27 15 17 37 MEDIUM MEDIUM 17 17 1 451 ; 1 polygons
*A ROAD STRONG LIGHT NONE SANITARY VCT S8 NO WM AC S6 NON 60 45 15 17 210 MEDIUM LOW 50 35 1 188 ; 1 polygons
*A ROAD STRONG LIGHT NONE STORM AC S8 NO WM PVC S8 NON 28 29 15 17 47 LOW HIGH 18 19 7 1,339 ; 1 polygons
*A ROAD STRONG LIGHT NONE STORM CONC S15 NO WM AC S6 NON 44 42 15 17 162 MEDIUM HIGH 34 32 15 421 ; 1 polygons
*A ROAD STRONG LIGHT NONE STORM CONC S15 NO WM CI S8 NON 44 55 15 17 128 LOW HIGH 34 45 1 380 ; 1 polygons
*A ROAD STRONG LIGHT NONE STORM CONC S15 NO WM CI S8 NON 44 55 15 17 93 HIGH MEDIUM 34 45 5 380 ; 1 polygons
*A ROAD STRONG LIGHT NONE STORM CONC S15 NO WM PVC S6 NON 44 50 15 17 94 LOW HIGH 34 40 5 372 ; 1 polygons
*A ROAD STRONG LIGHT NONE STORM CONC S15 NO WM UCI S6 NON 44 50 15 17 129 MEDIUM LOW 34 40 1 371 ; 1 polygons
*A ROAD STRONG LIGHT NONE STORM PVC S18 NO WM AC S6 NON 25 31 15 17 52 MEDIUM HIGH 15 21 13 738 ; 1 polygons
*A ROAD STRONG LIGHT NONE STORM PVC S18 NO WM PVC S6 NON 25 29 15 17 177 MEDIUM MEDIUM 15 19 7 649 ; 1 polygons
*A ROAD STRONG LIGHT NONE STORM PVC S18 NO WM PVC S8 NON 25 25 15 17 179 HIGH LOW 15 15 3 225 ; 1 polygons
*A ROAD STRONG LIGHT NONE STORM PVC S18 NO WM PVC S8 NON 25 29 15 17 176 LOW MEDIUM 15 19 7 1,215 ; 1 polygons
*A ROAD STRONG LIGHT NONE STORM PVC S8 NO WM AC S6 NON 35 35 15 17 61 LOW HIGH 25 25 9 824 ; 1 polygons
*A ROAD STRONG LIGHT NONE STORM VCT S12 NO WM PVC S6 NON 44 50 15 17 75 HIGH LOW 34 40 13 448 ; 1 polygons

*A ROAD STRONG LIGHT NONE STORM VCT S18 NO WM PVC S6 NON 25 2 15 17 171 MEDIUM LOW 15 8 7 899 ; 1 polygons
*A ROAD STRONG LIGHT NONE STORM VCT S8 NO WM AC S6 NON 46 46 15 17 55 LOW MEDIUM 36 36 9 669 ; 1 polygons
*A ROAD STRONG MEDIUM NONE SANITARY PVC S10 NO WM AC S8 NON 2 34 15 17 5 HIGH MEDIUM 8 24 7 656 ; 1 polygons
*A ROAD STRONG MEDIUM NONE STORM AC S8 NO WM CI S8 NON 46 51 15 17 188 MEDIUM LOW 36 41 5 236 ; 1 polygons
*A ROAD STRONG MEDIUM NONE STORM AC S8 NO WM CI S8 NON 46 51 15 17 189 MEDIUM LOW 36 41 5 236 ; 1 polygons
*A ROAD STRONG MEDIUM NONE STORM AC S8 NO WM PVC S8 NON 46 22 15 17 186 HIGH LOW 36 12 5 236 ; 1 polygons
*A ROAD STRONG MEDIUM NONE STORM CONC S15 NO WM CI S6 NON 46 54 15 17 169 LOW HIGH 36 44 5 369 ; 1 polygons
*A ROAD STRONG MEDIUM NONE STORM CONC S30 NO WM PVC S8 NON 46 22 15 17 101 LOW HIGH 36 12 5 238 ; 1 polygons
*A ROAD STRONG MEDIUM NONE STORM CONC S8 NO WM PVC S8 NON 46 22 15 17 185 MEDIUM HIGH 36 12 5 240 ; 1 polygons
*A ROAD WEAK LIGHT NONE SANITARY AC S6 NO WM AC S6 NON 36 42 15 17 262 HIGH MEDIUM 26 32 18 69 ; 1 polygons
*A ROAD WEAK LIGHT NONE SANITARY AC S8 NO WM PVC S8 NON 36 5 15 17 13 HIGH LOW 26 5 1 241 ; 1 polygons
*A ROAD WEAK LIGHT NONE SANITARY CONC S10 NO WM PVC S8 NON 60 5 15 17 205 LOW MEDIUM 50 5 7 239 ; 1 polygons
*A ROAD WEAK LIGHT NONE SANITARY CONC S8 NO WM AC S6 NON 50 46 15 17 207 MEDIUM HIGH 40 36 3 350 ; 1 polygons
*A ROAD WEAK LIGHT NONE SANITARY CONC S8 NO WM PVC S6 NON 50 50 15 17 221 HIGH LOW 40 40 18 677 ; 1 polygons
*A ROAD WEAK LIGHT NONE SANITARY PVC S8 NO WM CI S6 NON 1 1 15 17 46 MEDIUM HIGH 9 9 1 376 ; 1 polygons
*A ROAD WEAK LIGHT NONE SANITARY PVC S8 NO WM PVC S6 NON 50 9 15 17 45 HIGH MEDIUM 40 1 7 441 ; 1 polygons
*A ROAD WEAK LIGHT NONE SANITARY VCT S8 NO WM AC S6 NON 40 50 15 17 228 MEDIUM HIGH 30 40 18 346 ; 1 polygons
*A ROAD WEAK LIGHT NONE SANITARY VCT S8 NO WM AC S8 NON 60 40 15 17 206 MEDIUM MEDIUM 50 30 3 376 ; 1 polygons
*A ROAD WEAK LIGHT NONE SANITARY VCT S8 NO WM PVC S6 NON 50 26 15 17 222 MEDIUM HIGH 40 16 18 605 ; 1 polygons
*A ROAD WEAK LIGHT NONE STORM AC S8 NO WM PVC S8 NON 46 11 15 17 190 HIGH LOW 36 1 1 147 ; 1 polygons
*A ROAD WEAK LIGHT NONE STORM CONC S12 NO WM AC S6 NON 44 45 15 17 174 MEDIUM HIGH 34 35 10 509 ; 1 polygons
*A ROAD WEAK LIGHT NONE STORM CONC S12 NO WM PVC S8 NON 46 11 15 17 138 HIGH MEDIUM 36 1 7 381 ; 1 polygons
*A ROAD WEAK LIGHT NONE STORM CONC S12 NO WM PVC S8 NON 46 11 15 17 139 HIGH LOW 36 1 13 381 ; 1 polygons

*A ROAD WEAK LIGHT NONE STORM CONC S15 NO WM AC S6 NON 44 44 15 17 158 HIGH MEDIUM 34 34 11   201 ; 1 polygons
*A ROAD WEAK LIGHT NONE STORM CONC S15 NO WM AC S6 NON 44 44 15 17 89 MEDIUM HIGH 34 34 11   372 ; 1 polygons
*A ROAD WEAK LIGHT NONE STORM CONC S15 NO WM AC S6 NON 46 45 15 17 168 HIGH LOW 36 35 15   353 ; 1 polygons
*A ROAD WEAK LIGHT NONE STORM CONC S15 NO WM CI S6 NON 44 50 15 17 91 LOW MEDIUM 34 40 7   236 ; 1 polygons
*A ROAD WEAK LIGHT NONE STORM CONC S15 NO WM CI S6 NON 44 57 15 17 127 HIGH MEDIUM 34 47 7   236 ; 1 polygons
*A ROAD WEAK LIGHT NONE STORM CONC S15 NO WM CI S6 NON 46 58 15 17 133 MEDIUM MEDIUM 36 48 3   380 ; 1 polygons
*A ROAD WEAK LIGHT NONE STORM CONC S15 NO WM CI S6 NON 46 58 15 17 134 LOW MEDIUM 36 48 3   236 ; 1 polygons
*A ROAD WEAK LIGHT NONE STORM CONC S15 NO WM CI S8 NON 44 55 15 17 126 LOW MEDIUM 34 45 16   380 ; 1 polygons
*A ROAD WEAK LIGHT NONE STORM CONC S15 NO WM CI S8 NON 44 57 15 17 90 MEDIUM HIGH 34 47 7   380 ; 1 polygons
*A ROAD WEAK LIGHT NONE STORM CONC S15 NO WM PVC S8 NON 44 20 15 17 117 MEDIUM MEDIUM 34 10 1   240 ; 1 polygons
*A ROAD WEAK LIGHT NONE STORM CONC S15 NO WM PVC S8 NON 44 20 15 17 118 HIGH MEDIUM 34 10 3   236 ; 1 polygons
*A ROAD WEAK LIGHT NONE STORM CONC S15 NO WM PVC S8 NON 45 9 15 17 140 HIGH MEDIUM 35 1 7   376 ; 1 polygons
*A ROAD WEAK LIGHT NONE STORM CONC S15 NO WM PVC S8 NON 46 26 15 17 137 MEDIUM LOW 36 16 7   381 ; 1 polygons
*A ROAD WEAK LIGHT NONE STORM CONC S15 NO WM STEEL S8 NON 44 51 15 17 135 MEDIUM HIGH 34 41 1   381 ; 1 polygons
*A ROAD WEAK LIGHT NONE STORM CONC S15 NO WM UCI S6 NON 44 47 15 17 95 HIGH MEDIUM 34 37 7   376 ; 1 polygons
*A ROAD WEAK LIGHT NONE STORM CONC S15 NO WM UCI S6 NON 44 47 15 17 96 LOW HIGH 34 37 15   236 ; 1 polygons
*A ROAD WEAK LIGHT NONE STORM CONC S18 NO WM AC S6 NON 44 44 15 17 77 HIGH MEDIUM 34 34 9   236 ; 1 polygons
*A ROAD WEAK LIGHT NONE STORM CONC S18 NO WM AC S6 NON 44 44 15 17 84 HIGH LOW 34 34 7   372 ; 1 polygons
*A ROAD WEAK LIGHT NONE STORM CONC S18 NO WM CI S8 NON 44 57 15 17 83 HIGH MEDIUM 34 47 3   380 ; 1 polygons
*A ROAD WEAK LIGHT NONE STORM CONC S18 NO WM PVC S12 NON 45 20 15 17 116 MEDIUM HIGH 35 10 7   376 ; 1 polygons
*A ROAD WEAK LIGHT NONE STORM CONC S18 NO WM PVC S6 NON 44 16 15 17 88 HIGH LOW 34 6 3   376 ; 1 polygons
*A ROAD WEAK LIGHT NONE STORM CONC S18 NO WM PVC S6 NON 45 9 15 17 115 LOW HIGH 35 1 9   265 ; 1 polygons
*A ROAD WEAK LIGHT NONE STORM CONC S18 NO WM PVC S8 NON 46 22 15 17 107 MEDIUM HIGH 36 12 1   380 ; 1 polygons

*A ROAD WEAK LIGHT NONE STORM CONC S18 NO WM UCI S6 NON 44 50 15 17 78 LOW HIGH 34 40 15 440 ; 1 polygons
*A ROAD WEAK LIGHT NONE STORM CONC S18 NO WM UCI S6 NON 46 47 15 17 106 LOW HIGH 36 37 3 236 ; 1 polygons
*A ROAD WEAK LIGHT NONE STORM CONC S21 NO WM AC S6 NON 44 36 15 17 76 LOW HIGH 34 26 9 236 ; 1 polygons
*A ROAD WEAK LIGHT NONE STORM CONC S21 NO WM CI S6 NON 46 60 15 17 113 LOW HIGH 36 50 7 236 ; 1 polygons
*A ROAD WEAK LIGHT NONE STORM CONC S21 NO WM PVC S6 NON 46 27 15 17 108 MEDIUM LOW 36 17 7 241 ; 1 polygons
*A ROAD WEAK LIGHT NONE STORM CONC S21 NO WM PVC S8 NON 46 20 15 17 112 HIGH MEDIUM 36 10 9 376 ; 1 polygons
*A ROAD WEAK LIGHT NONE STORM CONC S21 NO WM PVC S8 NON 46 22 15 17 110 MEDIUM LOW 36 12 1 380 ; 1 polygons
*A ROAD WEAK LIGHT NONE STORM CONC S21 NO WM PVC S8 NON 46 26 15 17 104 MEDIUM HIGH 36 16 7 381 ; 1 polygons
*A ROAD WEAK LIGHT NONE STORM CONC S21 NO WM PVC S8 NON 46 26 15 17 111 HIGH MEDIUM 36 16 7 240 ; 1 polygons
*A ROAD WEAK LIGHT NONE STORM CONC S21 NO WM PVC S8 NON 46 27 15 17 109 HIGH LOW 36 17 7 380 ; 1 polygons
*A ROAD WEAK LIGHT NONE STORM CONC S24 NO WM PVC S8 NON 44 16 15 17 86 MEDIUM HIGH 34 6 11 238 ; 1 polygons
*A ROAD WEAK LIGHT NONE STORM CONC S24 NO WM PVC S8 NON 46 26 15 17 103 HIGH MEDIUM 36 16 1 381 ; 1 polygons
*A ROAD WEAK LIGHT NONE STORM CONC S30 NO WM PVC S8 NON 46 16 15 17 102 MEDIUM MEDIUM 36 6 7 238 ; 1 polygons
*A ROAD WEAK LIGHT NONE STORM CONC S8 NO WM AC S6 NON 44 44 15 17 194 MEDIUM LOW 34 34 16 235 ; 1 polygons
*A ROAD WEAK LIGHT NONE STORM CONC S8 NO WM CI S6 NON 44 50 15 17 197 MEDIUM MEDIUM 34 40 9 380 ; 1 polygons
*A ROAD WEAK LIGHT NONE STORM CONC S8 NO WM UCI S6 NON 44 50 15 17 49 MEDIUM HIGH 34 40 16 376 ; 1 polygons
*A ROAD WEAK LIGHT NONE STORM PVC S10 NO WM PVC S6 NON 20 29 15 17 64 HIGH LOW 10 19 18 473 ; 1 polygons
*A ROAD WEAK LIGHT NONE STORM PVC S12 NO WM PVC S8 NON 20 11 15 17 68 HIGH LOW 10 1 7 381 ; 1 polygons
*A ROAD WEAK LIGHT NONE STORM PVC S12 NO WM PVC S8 NON 20 11 15 17 70 HIGH MEDIUM 10 1 3 376 ; 1 polygons
*A ROAD WEAK LIGHT NONE STORM PVC S12 NO WM UCI S6 NON 20 60 15 17 69 LOW HIGH 10 50 3 236 ; 1 polygons
*A ROAD WEAK LIGHT NONE STORM PVC S8 NO WM PVC S6 NON 40 29 15 17 27 HIGH LOW 30 19 18 739 ; 1 polygons
*A ROAD WEAK LIGHT NONE STORM PVC S8 NO WM UCI S6 NON 44 50 15 17 1 HIGH LOW 34 40 8 236 ; 1 polygons
*A ROAD WEAK LIGHT NONE STORM VCT S10 NO WM AC S6 NON 44 45 15 17 153 HIGH MEDIUM 34 35 11 371 ; 1 polygons

*A ROAD WEAK LIGHT NONE STORM VCT S10 NO WM AC S6 NON 44 46 15 17 154 LOW MEDIUM 34 36 1   187 ; 1 polygons
*A ROAD WEAK LIGHT NONE STORM VCT S12 NO WM AC S6 NON 44 44 15 17 164 LOW HIGH 34 34 13   242 ; 1 polygons
*A ROAD WEAK LIGHT NONE STORM VCT S12 NO WM CI S6 NON 44 50 15 17 147 LOW HIGH 34 40 3   380 ; 1 polygons
*A ROAD WEAK LIGHT NONE STORM VCT S12 NO WM CI S6 NON 44 52 15 17 125 MEDIUM HIGH 34 42 7   236 ; 1 polygons
*A ROAD WEAK LIGHT NONE STORM VCT S12 NO WM CI S6 NON 44 57 15 17 123 MEDIUM LOW 34 47 15   371 ; 1 polygons
*A ROAD WEAK LIGHT NONE STORM VCT S12 NO WM CI S6 NON 44 58 15 17 131 MEDIUM HIGH 34 48 3   376 ; 1 polygons
*A ROAD WEAK LIGHT NONE STORM VCT S12 NO WM CI S8 NON 44 51 15 17 124 LOW HIGH 34 41 11   380 ; 1 polygons
*A ROAD WEAK LIGHT NONE STORM VCT S12 NO WM CI S8 NON 44 51 15 17 136 HIGH MEDIUM 34 41 13   376 ; 1 polygons
*A ROAD WEAK LIGHT NONE STORM VCT S12 NO WM CI S8 NON 44 51 15 17 148 HIGH LOW 34 41 7   236 ; 1 polygons
*A ROAD WEAK LIGHT NONE STORM VCT S12 NO WM CI S8 NON 44 51 15 17 149 LOW MEDIUM 34 41 11   381 ; 1 polygons
*A ROAD WEAK LIGHT NONE STORM VCT S12 NO WM PVC S6 NON 44 9 15 17 143 MEDIUM HIGH 34 1 7   236 ; 1 polygons
*A ROAD WEAK LIGHT NONE STORM VCT S12 NO WM PVC S6 NON 44 9 15 17 150 MEDIUM MEDIUM 34 1 7   230 ; 1 polygons
*A ROAD WEAK LIGHT NONE STORM VCT S12 NO WM PVC S8 NON 44 9 15 17 142 HIGH LOW 34 1 7   376 ; 1 polygons
*A ROAD WEAK LIGHT NONE STORM VCT S12 NO WM UCI S6 NON 44 50 15 17 121 MEDIUM HIGH 34 40 13   236 ; 1 polygons
*A ROAD WEAK LIGHT NONE STORM VCT S12 NO WM UCI S6 NON 44 58 15 17 130 MEDIUM MEDIUM 34 48 13   236 ; 1 polygons
*A ROAD WEAK LIGHT NONE STORM VCT S8 NO WM AC S6 NON 52 45 15 17 201 HIGH LOW 42 35 18   72 ; 1 polygons
*A ROAD WEAK MEDIUM NONE SANITARY VCT S10 NO WM AC S6 NON 45 42 15 17 215 HIGH MEDIUM 35 32 25   454 ; 1 polygons

8.5.3 *Lifespan*

; Lifespan

? 100

8.5.4 *Actions*

;-- Silo Intervention actions

;-- Road Interventions

*ACTION aCS Y
*OPERABLE aCS
ROADS ? ytPCIroads >= 99 and ytPCIroads <= 100

*ACTION aMS Y ;-- Microsurfacing - Pavement sealing and texturing to correct polished roadway surfaces. Binder rich mixtures (8.0% bitumen) with fine/medium aggregate in lifts of 8 to 10mm, which waterproof and seal existing surfaces
*OPERABLE aMS
ROADS ? ytPCIroads >= 85 and ytPCIroads <= 98

*ACTION aPA Y ;-- Spray/shallow Patching(PA) shallow patching involves heating old asphalt and adding new material as needed to ensure uniform pavement surface
*OPERABLE aPA
ROADS ? ytPCIroads >= 75 and ytPCIroads <= 85

*ACTION aRS Y ;-- Resurfacing (with full depth patching)(RS) need to define transition
*OPERABLE aRS
ROADS ? ytPCIroads >= 60 and ytPCIroads <= 75

*ACTION aRC Y ;--(RC) Reconstruction
*OPERABLE aRC
ROADS ? ytPCIroads >= 0 and ytPCIroads <= 60

*AGGREGATE aRepairROAD
aMS aRS aPA aRC aCS

;-- Sewer Interventions

*ACTION alinersewer_LD1 Y ;-- Low demand sewer plastic pipes
*OPERABLE alinersewer_LD1
? ? ? ? SEWER PLASTIC ? ? ? ? ? ? ? ? ? ? ? LOWDEMANDSEWER ? ? ? yreliabilitysr <= 120 and Ycapsewer <= 150

*ACTION alinersewer_LD2 Y ;-- Low demand sewer plastic pipes
*OPERABLE alinersewer_LD2
? ? ? ? SEWER PLASTIC ? ? ? ? ? ? ? ? ? ? ? LOWDEMANDSEWER ? ? ? yreliabilitysr <= 120 and Ycapsewer >= 150
? ? ? ? SEWER PLASTIC ? ? ? ? ? ? ? ? ? ? ? LOWDEMANDSEWER ? ? ? Ycapsewer >= 160

*ACTION alinersewer_HD1 Y ;-- High demand sewer plastic pipes
*OPERABLE alinersewer_HD1
? ? ? ? SEWER PLASTIC ? ? ? ? ? ? ? ? ? ? ? HIGH ? ? ? yreliabilitysr <= 140 and Ycapsewer <= 150

*ACTION alinersewer_HD2 Y ;-- High demand sewer plastic pipes
*OPERABLE alinersewer_HD2

? ? ? ? SEWER PLASTIC ? ? ? ? ? ? ? ? ? ? ? ? HIGH ? ? ? yreliabilitysr <= 140 and Ycapsewer >= 150
? ? ? ? SEWER PLASTIC ? ? ? ? ? ? ? ? ? ? ? ? HIGH ? ? ? Ycapsewer >= 160

*ACTION areplacesewer_LD1 Y
*OPERABLE areplacesewer_LD1
? ? ? ? SEWER ? ? ? ? ? ? ? ? ? ? ? ? LOWDEMANDSEWER ? ? ? yreliabilitysr <= 140 and Ycapsewer <= 150

*ACTION areplacesewer_LD2 Y
*OPERABLE areplacesewer_LD2
? ? ? ? SEWER ? ? ? ? ? ? ? ? ? ? ? ? LOWDEMANDSEWER ? ? ? yreliabilitysr <= 140 and Ycapsewer >= 150
? ? ? ? SEWER ? ? ? ? ? ? ? ? ? ? ? ? LOWDEMANDSEWER ? ? ? Ycapsewer >= 160

*ACTION areplacesewer_HD1 Y
*OPERABLE areplacesewer_HD1
? ? ? ? SEWER ? ? ? ? ? ? ? ? ? ? ? ? HIGH ? ? ? yreliabilitysr <= 140 and Ycapsewer <= 150

*ACTION areplacesewer_HD2 Y
*OPERABLE areplacesewer_HD2
? ? ? ? SEWER ? ? ? ? ? ? ? ? ? ? ? ? HIGH ? ? ? yreliabilitysr <= 140 and Ycapsewer >= 150
? ? ? ? SEWER ? ? ? ? ? ? ? ? ? ? ? ? HIGH ? ? ? Ycapsewer >= 160

*AGGREGATE aRepairsewer
alinersewer_LD1 alinersewer_LD2 alinersewer_HD1 alinersewer_HD2 areplacesewer_LD1 areplacesewer_LD2 areplacesewer_HD1 areplacesewer_HD2

; __ Water Interventions

*ACTION alinerwater_LD1 Y ;__ Low demand sewer plastic pipes
*OPERABLE alinerwater_LD1
? ? ? ? ? ? ? ? ? WM PLASTIC ? ? ? ? ? ? ? ? ? LOWDEMANDWATER ? ? yreliabilitywr <= 180 and Ycapwater <= 120

*ACTION alinerwater_LD2 Y ;__ Low demand sewer plastic pipes
*OPERABLE alinerwater_LD2
? ? ? ? ? ? ? ? ? WM PLASTIC ? ? ? ? ? ? ? ? ? LOWDEMANDWATER ? ? yreliabilitywr <= 180 and Ycapwater >= 120
? ? ? ? ? ? ? ? ? WM PLASTIC ? ? ? ? ? ? ? ? ? LOWDEMANDWATER ? ? Ycapwater >= 110

*ACTION alinerwater_HD1 Y ;__ High demand sewer plastic pipes
*OPERABLE alinerwater_HD1
? ? ? ? ? ? ? ? ? WM PLASTIC ? ? ? ? ? ? ? ? ? HIGH ? ? yreliabilitywr <= 180 and Ycapwater <= 100

*ACTION alinerwater_HD2 Y ;__ High demand sewer plastic pipes
*OPERABLE alinerwater_HD2
? ? ? ? ? ? ? ? WM PLASTIC ? ? ? ? ? ? ? ? HIGH ? ? yreliabilitywr <= 180 and Ycapwater >= 100
? ? ? ? ? ? ? ? WM PLASTIC ? ? ? ? ? ? ? ? HIGH ? ? Ycapwater >= 100

*ACTION areplacewater_LD1 Y
*OPERABLE areplacewater_LD1
? ? ? ? ? ? ? ? WM ? ? ? ? ? ? ? ? ? LOWDEMANDWATER ? ? yreliabilitywr <= 180 and Ycapwater <= 80

*ACTION areplacewater_LD2 Y
*OPERABLE areplacewater_LD2
? ? ? ? ? ? ? ? WM ? ? ? ? ? ? ? ? ? LOWDEMANDWATER ? ? yreliabilitywr <= 180 and Ycapwater >= 80
? ? ? ? ? ? ? ? WM ? ? ? ? ? ? ? ? ? LOWDEMANDWATER ? ? Ycapwater >= 110

*ACTION areplacewater_HD1 Y
*OPERABLE areplacewater_HD1
? ? ? ? ? ? ? ? WM ? ? ? ? ? ? ? ? ? HIGH ? ? yreliabilitywr <= 180 and Ycapwater <= 80

*ACTION areplacewater_HD2 Y
*OPERABLE areplacewater_HD2
? ? ? ? ? ? ? ? WM ? ? ? ? ? ? ? ? ? HIGH ? ? yreliabilitywr <= 180 and Ycapwater >= 80
? ? ? ? ? ? ? ? WM ? ? ? ? ? ? ? ? ? HIGH ? ? Ycapwater >= 110

*AGGREGATE aRepairwater
alinerwater_LD1 alinerwater_LD2 alinerwater_HD1 alinerwater_HD2 areplacewater_LD1 areplacewater_LD2 areplacewater_HD1 areplacewater_HD2

;__ Partially integrated intervention for roads and water

*ACTION aRDWR_LD1 Y
*OPERABLE aRDWR_LD1
ROADS ? ? ? ? ? ? ? WM ? ? ? ? ? ? ? ? ? LOWDEMANDWATER ? ? yreliabilitywr <= 200 and Ycapwater <= 100 and ytPCIroads <= 70

*ACTION aRDWR_LD2 Y
*OPERABLE aRDWR_LD2
ROADS ? ? ? ? ? ? ? WM ? ? ? ? ? ? ? ? ? LOWDEMANDWATER ? ? yreliabilitywr <= 200 and Ycapwater >= 100 and ytPCIroads <= 70
ROADS ? ? ? ? ? ? ? WM ? ? ? ? ? ? ? ? ? LOWDEMANDWATER ? ? Ycapwater >= 140

*ACTION aRDWR_HD1 Y
*OPERABLE aRDWR_HD1

ROADS ? ? ? ? ? ? ? WM ? ? ? ? ? ? ? ? ? HIGH ? ? yreliabilitywr <= 200 and Ycapwater <= 100 and ytPCIroads <= 70

*ACTION aRDWR_HD2 Y
*OPERABLE aRDWR_HD2
 ROADS ? ? ? ? ? ? ? WM ? ? ? ? ? ? ? ? ? HIGH ? ? yreliabilitywr <= 200 and Ycapwater >= 100 and ytPCIroads <= 70
 ROADS ? ? ? ? ? ? ? WM ? ? ? ? ? ? ? ? ? HIGH ? ? Ycapwater >= 150

*AGGREGATE aROADWATER
 aRDWR_LD1 aRDWR_LD2 aRDWR_HD1 aRDWR_HD2

;__ Partially integrated intervention for roads and sewer

*ACTION aRDSR_LD1 Y
*OPERABLE aRDSR_LD1
 ROADS ? ? ? SEWER ? ? ? ? ? ? ? ? ? ? ? ? LOWDEMANDSEWER ? ? ? yreliabilitysr <= 150 and Ycapsewer <= 80 and ytPCIroads <= 70

*ACTION aRDSR_LD2 Y
*OPERABLE aRDSR_LD2
 ROADS ? ? ? SEWER ? ? ? ? ? ? ? ? ? ? ? ? LOWDEMANDSEWER ? ? ? yreliabilitysr <= 150 and Ycapsewer >= 80 and ytPCIroads <= 70
 ROADS ? ? ? SEWER ? ? ? ? ? ? ? ? ? ? ? ? LOWDEMANDSEWER ? ? ? Ycapsewer >= 85

*ACTION aRDSR_HD1 Y
*OPERABLE aRDSR_HD1
 ROADS ? ? ? SEWER ? ? ? ? ? ? ? ? ? ? ? ? HIGH ? ? ? yreliabilitysr <= 150 and Ycapsewer <= 80 and ytPCIroads <= 70

*ACTION aRDSR_HD2 Y
*OPERABLE aRDSR_HD2
 ROADS ? ? ? SEWER ? ? ? ? ? ? ? ? ? ? ? ? HIGH ? ? ? yreliabilitysr <= 150 and Ycapsewer >= 80 and ytPCIroads <= 70
 ROADS ? ? ? SEWER ? ? ? ? ? ? ? ? ? ? ? ? HIGH ? ? ? Ycapsewer >= 75

*AGGREGATE aROADSEWER
 aRDSR_LD1 aRDSR_LD2 aRDSR_HD1 aRDSR_HD2

;__ Partially integrated intervention for water and sewer (Trenchless not to impact the road)

*ACTION aSRWR_LD1_LD1 Y
*OPERABLE aSRWR_LD1_LD1
 ? ? ? ? SEWER ? ? ? WM ? ? ? ? ? ? ? ? LOWDEMANDSEWER LOWDEMANDWATER ? ? yreliabilitysr <= 150 and Ycapsewer <= 50 and yreliabilitywr <= 150 and Ycapwater <= 50

*ACTION aSRWR_LD1_LD2 Y
*OPERABLE aSRWR_LD1_LD2
? ? ? ? SEWER ? ? ? WM ? ? ? ? ? ? ? ? LOWDEMANDSEWER LOWDEMANDWATER ? ? yreliabilitysr <= 150 and Ycapsewer <= 50 and yreliabilitywr <= 150 and Ycapwater >= 50
? ? ? ? SEWER ? ? ? WM ? ? ? ? ? ? ? ? LOWDEMANDSEWER LOWDEMANDWATER ? ? Ycapsewer >= 85 and Ycapwater >= 70

*ACTION aSRWR_LD2_LD1 Y
*OPERABLE aSRWR_LD2_LD1
? ? ? ? SEWER ? ? ? WM ? ? ? ? ? ? ? ? LOWDEMANDSEWER LOWDEMANDWATER ? ? yreliabilitysr <= 150 and Ycapsewer >= 50 and yreliabilitywr <= 150 and Ycapwater <= 50
? ? ? ? SEWER ? ? ? WM ? ? ? ? ? ? ? ? LOWDEMANDSEWER LOWDEMANDWATER ? ? Ycapsewer >= 85 and Ycapwater >= 70

*ACTION aSRWR_LD2_LD2 Y
*OPERABLE aSRWR_LD2_LD2
? ? ? ? SEWER ? ? ? WM ? ? ? ? ? ? ? ? LOWDEMANDSEWER LOWDEMANDWATER ? ? yreliabilitysr <= 150 and Ycapsewer >= 50 and yreliabilitywr <= 150 and Ycapwater >= 50
? ? ? ? SEWER ? ? ? WM ? ? ? ? ? ? ? ? LOWDEMANDSEWER LOWDEMANDWATER ? ? Ycapsewer >= 85 and Ycapwater >= 85

*ACTION aSRWR_HD1_HD1 Y
*OPERABLE aSRWR_HD1_HD1
? ? ? ? SEWER ? ? ? WM ? ? ? ? ? ? ? ? HIGH HIGH ? ? yreliabilitysr <= 150 and Ycapsewer <= 40 and yreliabilitywr <= 150 and Ycapwater <= 40

*ACTION aSRWR_HD1_HD2 Y
*OPERABLE aSRWR_HD1_HD2
? ? ? ? SEWER ? ? ? WM ? ? ? ? ? ? ? ? HIGH HIGH ? ? yreliabilitysr <= 150 and Ycapsewer <= 40 and yreliabilitywr <= 150 and Ycapwater >= 40
? ? ? ? SEWER ? ? ? WM ? ? ? ? ? ? ? ? HIGH HIGH ? ? Ycapsewer >= 75 and Ycapwater >= 60

*ACTION aSRWR_HD2_HD1 Y
*OPERABLE aSRWR_HD2_HD1
? ? ? ? SEWER ? ? ? WM ? ? ? ? ? ? ? ? HIGH HIGH ? ? yreliabilitysr <= 150 and Ycapsewer >= 40 and yreliabilitywr <= 150 and Ycapwater <= 40
? ? ? ? SEWER ? ? ? WM ? ? ? ? ? ? ? ? HIGH HIGH ? ? Ycapsewer >= 75 and Ycapwater >= 60

*ACTION aSRWR_HD2_HD2 Y
*OPERABLE aSRWR_HD2_HD2
? ? ? ? SEWER ? ? ? WM ? ? ? ? ? ? ? ? HIGH HIGH ? ? yreliabilitysr <= 150 and Ycapsewer >= 40 and yreliabilitywr <= 150 and Ycapwater >= 40
? ? ? ? SEWER ? ? ? WM ? ? ? ? ? ? ? ? HIGH HIGH ? ? Ycapsewer >= 75 and Ycapwater >= 75

*ACTION aSRWR_LD1_HD1 Y
*OPERABLE aSRWR_LD1_HD1
? ? ? ? SEWER ? ? ? WM ? ? ? ? ? ? ? ? ? LOWDEMANDSEWER HIGH ? ? yreliabilitysr <= 150 and Ycapsewer <= 50 and yreliabilitywr <= 150 and Ycapwater <= 40

*ACTION aSRWR_LD1_HD2 Y
*OPERABLE aSRWR_LD1_HD2
? ? ? ? SEWER ? ? ? WM ? ? ? ? ? ? ? ? ? LOWDEMANDSEWER HIGH ? ? yreliabilitysr <= 150 and Ycapsewer <= 50 and yreliabilitywr <= 150 and Ycapwater >= 40
? ? ? ? SEWER ? ? ? WM ? ? ? ? ? ? ? ? ? LOWDEMANDSEWER HIGH ? ? Ycapwater >= 75 and Ycapwater >= 60

*ACTION aSRWR_LD2_HD1 Y
*OPERABLE aSRWR_LD2_HD1
? ? ? ? SEWER ? ? ? WM ? ? ? ? ? ? ? ? ? LOWDEMANDSEWER HIGH ? ? yreliabilitysr <= 150 and Ycapsewer >= 50 and yreliabilitywr <= 150 and Ycapwater <= 40
? ? ? ? SEWER ? ? ? WM ? ? ? ? ? ? ? ? ? LOWDEMANDSEWER HIGH ? ? Ycapsewer >= 75 and Ycapwater >= 60

*ACTION aSRWR_LD2_HD2 Y
*OPERABLE aSRWR_LD2_HD2
? ? ? ? SEWER ? ? ? WM ? ? ? ? ? ? ? ? ? LOWDEMANDSEWER HIGH ? ? yreliabilitysr <= 150 and Ycapsewer >= 50 and yreliabilitywr <= 150 and Ycapwater >= 40
? ? ? ? SEWER ? ? ? WM ? ? ? ? ? ? ? ? ? LOWDEMANDSEWER HIGH ? ? Ycapsewer >= 75 and Ycapwater >= 75

*ACTION aSRWR_HD1_LD1 Y
*OPERABLE aSRWR_HD1_LD1
? ? ? ? SEWER ? ? ? WM ? ? ? ? ? ? ? ? ? HIGH LOWDEMANDWATER ? ? yreliabilitysr <= 150 and Ycapsewer <= 40 and yreliabilitywr <= 150 and Ycapwater <= 50

*ACTION aSRWR_HD1_LD2 Y
*OPERABLE aSRWR_HD1_LD2
? ? ? ? SEWER ? ? ? WM ? ? ? ? ? ? ? ? ? HIGH LOWDEMANDWATER ? ? yreliabilitysr <= 150 and Ycapsewer <= 40 and yreliabilitywr <= 150 and Ycapwater >= 50
? ? ? ? SEWER ? ? ? WM ? ? ? ? ? ? ? ? ? HIGH LOWDEMANDWATER ? ? Ycapsewer >= 75 and Ycapwater >= 70

*ACTION aSRWR_HD2_LD1 Y
*OPERABLE aSRWR_HD2_LD1
? ? ? ? SEWER ? ? ? WM ? ? ? ? ? ? ? ? ? HIGH LOWDEMANDWATER ? ? yreliabilitysr <= 150 and Ycapsewer >= 40 and yreliabilitywr <= 150 and Ycapwater <= 50
? ? ? ? SEWER ? ? ? WM ? ? ? ? ? ? ? ? ? HIGH LOWDEMANDWATER ? ? Ycapsewer >= 75 and Ycapwater >= 70

*ACTION aSRWR_HD2_LD2 Y
*OPERABLE aSRWR_HD2_LD2
? ? ? ? SEWER ? ? ? WM ? ? ? ? ? ? ? ? ? HIGH LOWDEMANDWATER ? ? yreliabilitysr <= 150 and Ycapsewer >= 40 and yreliabilitywr <= 150 and Ycapwater >= 50
? ? ? ? SEWER ? ? ? WM ? ? ? ? ? ? ? ? ? HIGH LOWDEMANDWATER ? ? Ycapsewer >= 75 and Ycapwater >= 85

*AGGREGATE aSEWERWATER
aSRWR_LD1_LD1 aSRWR_LD1_LD2 aSRWR_LD2_LD1 aSRWR_LD2_LD2 aSRWR_HD1_HD1 aSRWR_HD1_HD2 aSRWR_HD2_HD1 aSRWR_HD2_HD2 aSRWR_LD1_HD1 aSRWR_LD1_HD2 aSRWR_LD2_HD1 aSRWR_LD2_HD2 aSRWR_HD1_LD1 aSRWR_HD1_LD2 aSRWR_HD2_LD1 aSRWR_HD2_LD2

*AGGREGATE aSEWERWATER
aSRWR_LD1_LD1 aSRWR_LD1_LD2 aSRWR_LD2_LD1 aSRWR_LD2_LD2 aSRWR_HD1_HD1 aSRWR_HD1_HD2 aSRWR_HD2_HD1 aSRWR_HD2_HD2 aSRWR_LD1_HD1 aSRWR_LD1_HD2 aSRWR_LD2_HD1 aSRWR_LD2_HD2 aSRWR_HD1_LD1 aSRWR_HD1_LD2 aSRWR_HD2_LD1 aSRWR_HD2_LD2

;__ Fully integrated intervention for roads, water and sewer

*ACTION aRWS_LD1_LD1 Y
*OPERABLE aRWS_LD1_LD1
ROADS ? ? ? SEWER ? ? ? WM ? ? ? ? ? ? ? ? LOWDEMANDSEWER LOWDEMANDWATER ? ? yreliabilitysr <= 150 and Ycapsewer <= 50 and yreliabilitywr <= 200 and Ycapwater <= 50 and ytpciroads <= 75

*ACTION aRWS_LD1_LD2 Y
*OPERABLE aRWS_LD1_LD2
ROADS ? ? ? SEWER ? ? ? WM ? ? ? ? ? ? ? ? LOWDEMANDSEWER LOWDEMANDWATER ? ? yreliabilitysr <= 100 and Ycapsewer <= 50 and yreliabilitywr <= 200 and Ycapwater >= 50 and ytpciroads <= 75
ROADS ? ? ? SEWER ? ? ? WM ? ? ? ? ? ? ? ? LOWDEMANDSEWER LOWDEMANDWATER ? ? Ycapsewer >= 85 and Ycapwater >= 70

*ACTION aRWS_LD2_LD1 Y
*OPERABLE aRWS_LD2_LD1
ROADS ? ? ? SEWER ? ? ? WM ? ? ? ? ? ? ? ? LOWDEMANDSEWER LOWDEMANDWATER ? ? yreliabilitysr <= 100 and Ycapsewer >= 50 and yreliabilitywr <= 200 and Ycapwater <= 50 and ytpciroads <= 75
ROADS ? ? ? SEWER ? ? ? WM ? ? ? ? ? ? ? ? LOWDEMANDSEWER LOWDEMANDWATER ? ? Ycapsewer >= 85 and Ycapwater >= 70

*ACTION aRWS_LD2_LD2 Y
*OPERABLE aRWS_LD2_LD2

ROADS ? ? ? SEWER ? ? ? WM ? ? ? ? ? ? ? ? LOWDEMANDSEWER LOWDEMANDWATER ? ? yreliabilitysr <= 100 and Ycapsewer >= 50 and yreliabilitywr <= 200 and Ycapwater >= 50 and ytpciroads <= 75
ROADS ? ? ? SEWER ? ? ? WM ? ? ? ? ? ? ? ? LOWDEMANDSEWER LOWDEMANDWATER ? ? Ycapsewer >= 85 and Ycapwater >= 85

*ACTION aRWS_HD1_HD1 Y
*OPERABLE aRWS_HD1_HD1
ROADS ? ? ? SEWER ? ? ? WM ? ? ? ? ? ? ? ? HIGH HIGH ? ? yreliabilitysr <= 100 and Ycapsewer <= 40 and yreliabilitywr <= 200 and Ycapwater <= 40 and ytpciroads <= 75

*ACTION aRWS_HD1_HD2 Y
*OPERABLE aRWS_HD1_HD2
ROADS ? ? ? SEWER ? ? ? WM ? ? ? ? ? ? ? ? HIGH HIGH ? ? yreliabilitysr <= 100 and Ycapsewer <= 40 and yreliabilitywr <= 200 and Ycapwater >= 40 and ytpciroads <= 75
ROADS ? ? ? SEWER ? ? ? WM ? ? ? ? ? ? ? ? HIGH HIGH ? ? Ycapsewer >= 75 and Ycapwater >= 60

*ACTION aRWS_HD2_HD1 Y
*OPERABLE aRWS_HD2_HD1
ROADS ? ? ? SEWER ? ? ? WM ? ? ? ? ? ? ? ? HIGH HIGH ? ? yreliabilitysr <= 100 and Ycapsewer >= 40 and yreliabilitywr <= 200 and Ycapwater <= 40 and ytpciroads <= 75
ROADS ? ? ? SEWER ? ? ? WM ? ? ? ? ? ? ? ? HIGH HIGH ? ? Ycapsewer >= 75 and Ycapwater >= 60

*ACTION aRWS_HD2_HD2 Y
*OPERABLE aRWS_HD2_HD2
ROADS ? ? ? SEWER ? ? ? WM ? ? ? ? ? ? ? ? HIGH HIGH ? ? yreliabilitysr <= 100 and Ycapsewer >= 40 and yreliabilitywr <= 200 and Ycapwater >= 40 and ytpciroads <= 75
ROADS ? ? ? SEWER ? ? ? WM ? ? ? ? ? ? ? ? HIGH HIGH ? ? Ycapsewer >= 75 and Ycapwater >= 75

*ACTION aRWS_LD1_HD1 Y
*OPERABLE aRWS_LD1_HD1
ROADS ? ? ? SEWER ? ? ? WM ? ? ? ? ? ? ? ? LOWDEMANDSEWER HIGH ? ? yreliabilitysr <= 100 and Ycapsewer <= 50 and yreliabilitywr <= 200 and Ycapwater <= 40 and ytpciroads <= 75

*ACTION aRWS_LD1_HD2 Y
*OPERABLE aRWS_LD1_HD2
ROADS ? ? ? SEWER ? ? ? WM ? ? ? ? ? ? ? ? LOWDEMANDSEWER HIGH ? ? yreliabilitysr <= 100 and Ycapsewer <= 50 and yreliabilitywr <= 200 and Ycapwater >= 40 and ytpciroads <= 75
ROADS ? ? ? SEWER ? ? ? WM ? ? ? ? ? ? ? ? LOWDEMANDSEWER HIGH ? ? Ycapwater >= 75 and Ycapwater >= 60

*ACTION aRWS_LD2_HD1 Y
*OPERABLE aRWS_LD2_HD1
ROADS ? ? ? SEWER ? ? ? WM ? ? ? ? ? ? ? ? LOWDEMANDSEWER HIGH ? ? yreliabilitysr <= 100 and Ycapsewer >= 50 and yreliabilitywr <= 200 and Ycapwater <= 40 and ytpciroads <= 75
ROADS ? ? ? SEWER ? ? ? WM ? ? ? ? ? ? ? ? LOWDEMANDSEWER HIGH ? ? Ycapsewer >= 75 and Ycapwater >= 60

*ACTION aRWS_LD2_HD2 Y
*OPERABLE aRWS_LD2_HD2
ROADS ? ? ? SEWER ? ? ? WM ? ? ? ? ? ? ? ? LOWDEMANDSEWER HIGH ? ? yreliabilitysr <= 100 and Ycapsewer >= 50 and yreliabilitywr <= 200 and Ycapwater >= 40 and ytpciroads <= 75
ROADS ? ? ? SEWER ? ? ? WM ? ? ? ? ? ? ? ? LOWDEMANDSEWER HIGH ? ? Ycapsewer >= 75 and Ycapwater >= 75

*ACTION aRWS_HD1_LD1 Y
*OPERABLE aRWS_HD1_LD1
ROADS ? ? ? SEWER ? ? ? WM ? ? ? ? ? ? ? ? HIGH LOWDEMANDWATER ? ? yreliabilitysr <= 100 and Ycapsewer <= 40 and yreliabilitywr <= 200 and Ycapwater <= 50 and ytpciroads <= 75

*ACTION aRWS_HD1_LD2 Y
*OPERABLE aRWS_HD1_LD2
ROADS ? ? ? SEWER ? ? ? WM ? ? ? ? ? ? ? ? HIGH LOWDEMANDWATER ? ? yreliabilitysr <= 100 and Ycapsewer <= 40 and yreliabilitywr <= 200 and Ycapwater >= 50 and ytpciroads <= 75
ROADS ? ? ? SEWER ? ? ? WM ? ? ? ? ? ? ? ? HIGH LOWDEMANDWATER ? ? Ycapsewer >= 75

8.5.5 *Transitions*

; Transitions

; Transitions

;-----------TRANSITIONS ROADS------------------

*CASE aCS
*SOURCE ROADS ?
*TARGET ? ? ? CS ? ? ? ? ? ? ? ? ? ? ? ? ? ? ? ? ? 80 _AGE 8 _LOCK 4
*TARGET ? ? ? CS ? ? ? ? ? ? ? ? ? ? ? ? ? ? ? ? ? 20 _AGE 9 _LOCK 4

*CASE aMS
*SOURCE ROADS ?
*TARGET ? ? ? MS ? ? ? ? ? ? ? ? ? ? ? ? ? ? ? ? ? 80 _AGE 9 _LOCK 5
*TARGET ? ? ? MS ? ? ? ? ? ? ? ? ? ? ? ? ? ? ? ? ? 20 _AGE 11 _LOCK 5

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*CASE aPA
*SOURCE ROADS ? ? ? ? ? ? ? ? ? ? ? ? ? ? ? ? ? ? ? ? ?
 *TARGET ? ? ? PA ? ? ? ? ? ? ? ? ? ? ? ? ? ? ? ? ? ? 80 _AGE 10  _LOCK 6
 *TARGET ? ? ? PA ? ? ? ? ? ? ? ? ? ? ? ? ? ? ? ? ? ? 20 _AGE 13 _LOCK 6

*CASE aRS
*SOURCE ROADS ? ? ? ? ? ? ? ? ? ? ? ? ? ? ? ? ? ? ? ? ?
 *TARGET ? ? ? RS ? ? ? ? ? ? ? ? ? ? ? ? ? ? ? ? ? ? 80 _AGE 7  _LOCK 8
 *TARGET ? ? ? RS ? ? ? ? ? ? ? ? ? ? ? ? ? ? ? ? ? ? 20 _AGE 11 _LOCK 8

*CASE aRC
*SOURCE ROADS ? ? ? ? ? ? ? ? ? ? ? ? ? ? ? ? ? ? ? ? ?
 *TARGET ? ? ? RC ? ? ? ? ? ? ? ? ? ? ? ? ? ? ? ? ? ? 80 _AGE 1 _LOCK 10
 *TARGET ? ? ? RC ? ? ? ? ? ? ? ? ? ? ? ? ? ? ? ? ? ? 20 _AGE 3 _LOCK 10

;-----------------------TRANSITIONS SEWER PIPES--------------------

*CASE alinersewer_LD1
*SOURCE ? ? ? ? SEWER PLASTIC ? ? ? ? ? ? ? ? ? ? ? LOWDEMANDSEWER ? ? ?
 *TARGET ? ? ? linersewer ? ? ? ? ? ? ? ? ? -1 ? ? ? ? ? ? ?  100 _LOCK 5

*CASE alinersewer_LD2
*SOURCE ? ? ? ? SEWER PLASTIC ? ? ? ? ? ? ? ? ? ? ? LOWDEMANDSEWER ? ? ?
 *TARGET ? ? ? linersewer ? ? ? ? ? ? ? ? ? -1 ? ? ? ? ? 1 ?  100 _LOCK 5

*CASE alinersewer_HD1
*SOURCE ? ? ? ? SEWER PLASTIC ? ? ? ? ? ? ? ? ? ? ? HIGH ? ? ?
 *TARGET ? ? ? linersewer ? ? ? ? ? ? ? ? ? -1 ? ? ? HIGH ? ? ? 100 _LOCK 5

*CASE alinersewer_HD2
*SOURCE ? ? ? ? SEWER PLASTIC ? ? ? ? ? ? ? ? ? ? ? HIGH ? ? ?
 *TARGET ? ? ? linersewer ? ? ? ? ? ? ? ? ? -1 ? ? ? HIGH ? 1 ?  100 _LOCK 5

*CASE areplacesewer_LD1
*SOURCE ? ? ? ? SEWER ? ? ? ? ? ? ? ? ? ? ? ? LOWDEMANDSEWER ? ? ?
 *TARGET ? ? ? replacesewer ? ? ? ? ? ? ? ? ? -1 ? ? ? ? ? ? ? 100 _LOCK 5

*CASE areplacesewer_LD2
*SOURCE ? ? ? ? SEWER ? ? ? ? ? ? ? ? ? ? ? ? LOWDEMANDSEWER ? ? ?
 *TARGET ? ? ? replacesewer ? ? ? ? ? ? ? ? ? -1 ? ? ? ? ? 1 ? 100 _LOCK 5

*CASE areplacesewer_HD1
*SOURCE ? ? ? ? SEWER ? ? ? ? ? ? ? ? ? ? ? ? HIGH ? ? ?
 *TARGET ? ? ? replacesewer ? ? ? ? ? ? ? ? ? -1 ? ? ? HIGH ? ? ? 100 _LOCK 5
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*CASE areplacesewer_HD2
*SOURCE ? ? ? ? SEWER ? ? ? ? ? ? ? ? ? ? ? ? HIGH ? ? ?
 *TARGET ? ? ? replacesewer ? ? ? ? ? ? ? ? ? -1 ? ? ? HIGH ? 1 ? 100 _LOCK 5

;----------------------TRANSITIONS WATER PIPES-------------------

*CASE alinerwater_LD1
*SOURCE ? ? ? ? ? ? ? ? WM PLASTIC ? ? ? ? ? ? ? ? LOWDEMANDWATER ? ?
 *TARGET ? ? ? linerwater ? ? ? ? WM ? ? ? -1 -1 ? ? ? ? ? ? ? 100 _LOCK 5

*CASE alinerwater_LD2
*SOURCE ? ? ? ? ? ? ? ? WM PLASTIC ? ? ? ? ? ? ? ? LOWDEMANDWATER ? ?
 *TARGET ? ? ? linerwater ? ? ? ? WM ? ? ? -1 -1 ? ? ? ? ? ? 1  100 _LOCK 5

*CASE alinerwater_HD1
*SOURCE ? ? ? ? ? ? ? ? WM PLASTIC ? ? ? ? ? ? ? ? HIGH ? ?
 *TARGET ? ? ? linerwater ? ? ? ? WM ? ? ? -1 -1 ? ? ? ? HIGH ? ? 100 _LOCK 5

*CASE alinerwater_HD2
*SOURCE ? ? ? ? ? ? ? ? WM PLASTIC ? ? ? ? ? ? ? ? HIGH ? ?
 *TARGET ? ? ? linerwater ? ? ? ? WM ? ? ? -1 -1 ? ? ? ? HIGH ? 1 100 _LOCK 5

*CASE areplacewater_LD1
*SOURCE ? ? ? ? ? ? ? ? WM ? ? ? ? ? ? ? ? ? LOWDEMANDWATER ? ?
 *TARGET ? ? ? replacewater ? ? ? ? WM ? ? ? -1 -1 ? ? ? ? ? ? ? 100 _LOCK 5

*CASE areplacewater_LD2
*SOURCE ? ? ? ? ? ? ? ? WM ? ? ? ? ? ? ? ? ? LOWDEMANDWATER ? ?
 *TARGET ? ? ? replacewater ? ? ? ? WM ? ? ? -1 -1 ? ? ? ? ? ? 1 100 _LOCK 5

*CASE areplacewater_HD1
*SOURCE ? ? ? ? ? ? ? ? WM ? ? ? ? ? ? ? ? ? HIGH ? ?
 *TARGET ? ? ? replacewater ? ? ? ? WM ? ? ? -1 -1 ? ? ? ? HIGH ? ? 100 _LOCK 5

*CASE areplacewater_HD2
*SOURCE ? ? ? ? ? ? ? ? WM ? ? ? ? ? ? ? ? ? HIGH ? ?
 *TARGET ? ? ? replacewater ? ? ? ? WM ? ? ? -1 -1 ? ? ? ? HIGH ? 1 100 _LOCK 5

;----------------------TRANSITIONS ROADS AND WATER PIPES-------

*CASE aRDWR_LD1
*SOURCE ROADS ? ? ? ? ? ? ? WM ? ? ? ? ? ? ? ? ? LOWDEMANDWATER ? ?
 *TARGET ? ? ? ? ? ? ? RDWR WM ? ? ? ? -1 ? ? ? ? ? ? ? 100 _AGE 1 _LOCK 5

*CASE aRDWR_LD2
*SOURCE ROADS ? ? ? ? ? ? ? WM ? ? ? ? ? ? ? ? ? LOWDEMANDWATER ? ?
```

*TARGET ? ? ? ? ? ? ? RDWR WM ? ? ? ? -1 ? ? ? ? ? ? ? 1 100 _AGE 1 _LOCK 5

*CASE aRDWR_HD1
*SOURCE ROADS ? ? ? ? ? ? ? WM ? ? ? ? ? ? ? ? ? HIGH ? ?
*TARGET ? ? ? ? ? ? ? RDWR WM ? ? ? ? -1 ? ? ? ? HIGH ? ? 100 _AGE 1 _LOCK 5

*CASE aRDWR_HD2
*SOURCE ROADS ? ? ? ? ? ? ? WM ? ? ? ? ? ? ? ? ? HIGH ? ?
*TARGET ? ? ? ? ? ? ? RDWR WM ? ? ? ? -1 ? ? ? ? HIGH ? 1 100 _AGE 1 _LOCK 5

;---------------------TRANSITIONS ROADS AND SEWER PIPES-------

*CASE aRDSR_LD1
*SOURCE ROADS ? ? ? SEWER ? ? ? ? ? ? ? ? ? ? ? ? LOWDEMANDSEWER ? ? ?
*TARGET ? ? ? ? ? ? ? RDSR ? ? ? ? -1 ? ? ? ? ? ? ? ? ? 100 _AGE 1 _LOCK 5

*CASE aRDSR_LD2
*SOURCE ROADS ? ? ? SEWER ? ? ? ? ? ? ? ? ? ? ? ? LOWDEMANDSEWER ? ? ?
*TARGET ? ? ? ? ? ? ? RDSR ? ? ? ? -1 ? ? ? ? ? ? ? 1 ? 100 _AGE 1 _LOCK 5

*CASE aRDSR_HD1
*SOURCE ROADS ? ? ? SEWER ? ? ? ? ? ? ? ? ? ? ? ? HIGH ? ? ?
*TARGET ? ? ? ? ? ? ? RDSR ? ? ? ? -1 ? ? ? ? HIGH ? ? ? 100 _AGE 1 _LOCK 5

*CASE aRDSR_HD2
*SOURCE ROADS ? ? ? SEWER ? ? ? ? ? ? ? ? ? ? ? ? HIGH ? ? ?
*TARGET ? ? ? ? ? ? ? RDSR ? ? ? ? -1 ? ? ? ? HIGH ? 1 ? 100 _AGE 1 _LOCK 5

;---------------------TRANSITIONS WATER AND SEWER PIPES-------

*CASE aSRWR_LD1_LD1
*SOURCE ? ? ? ? SEWER ? ? ? WM ? ? ? ? ? ? ? ? LOWDEMANDSEWER LOWDEMANDWATER ? ?
*TARGET ? ? ? ? ? ? ? SRWR WM ? ? ? -1 -1 ? ? ? ? ? ? ? ? 100 _LOCK 5

*CASE aSRWR_LD1_LD2
*SOURCE ? ? ? ? SEWER ? ? ? WM ? ? ? ? ? ? ? ? LOWDEMANDSEWER LOWDEMANDWATER ? ?
*TARGET ? ? ? ? ? ? ? SRWR WM ? ? ? -1 -1 ? ? ? ? ? ? ? 1 100 _LOCK 5

*CASE aSRWR_LD2_LD1
*SOURCE ? ? ? ? SEWER ? ? ? WM ? ? ? ? ? ? ? ? LOWDEMANDSEWER LOWDEMANDWATER ? ?
*TARGET ? ? ? ? ? ? ? SRWR WM ? ? ? -1 -1 ? ? ? ? ? ? 1 ? 100 _LOCK 5

*CASE aSRWR_LD2_LD2

*SOURCE ? ? ? ? SEWER ? ? ? WM ? ? ? ? ? ? ? ? LOWDEMANDSEWER LOWDEMANDWATER ? ?
*TARGET ? ? ? ? ? ? ? SRWR WM ? ? ? -1 -1 ? ? ? ? ? 1 1 100 _LOCK 5

*CASE aSRWR_HD1_HD1
*SOURCE ? ? ? ? SEWER ? ? ? WM ? ? ? ? ? ? ? ? HIGH HIGH ? ?
*TARGET ? ? ? ? ? ? ? SRWR WM ? ? ? -1 -1 ? ? ? HIGH HIGH ? ? 100 _LOCK 5

*CASE aSRWR_HD1_HD2
*SOURCE ? ? ? ? SEWER ? ? ? WM ? ? ? ? ? ? ? ? HIGH HIGH ? ?
*TARGET ? ? ? ? ? ? ? SRWR WM ? ? ? -1 -1 ? ? ? HIGH HIGH ? 1 100 _LOCK 5

*CASE aSRWR_HD2_HD1
*SOURCE ? ? ? ? SEWER ? ? ? WM ? ? ? ? ? ? ? ? HIGH HIGH ? ?
*TARGET ? ? ? ? ? ? ? SRWR WM ? ? ? -1 -1 ? ? ? HIGH HIGH 1 ? 100 _LOCK 5

*CASE aSRWR_HD2_HD2
*SOURCE ? ? ? ? SEWER ? ? ? WM ? ? ? ? ? ? ? ? HIGH HIGH ? ?
*TARGET ? ? ? ? ? ? ? SRWR WM ? ? ? -1 -1 ? ? ? HIGH HIGH 1 1 100 _LOCK 5

*CASE aSRWR_LD1_HD1
*SOURCE ? ? ? ? SEWER ? ? ? WM ? ? ? ? ? ? ? ? LOWDEMANDSEWER HIGH ? ?
*TARGET ? ? ? ? ? ? ? SRWR WM ? ? ? -1 -1 ? ? ? ? HIGH ? ? 100 _LOCK 5

*CASE aSRWR_LD1_HD2
*SOURCE ? ? ? ? SEWER ? ? ? WM ? ? ? ? ? ? ? ? LOWDEMANDSEWER HIGH ? ?
*TARGET ? ? ? ? ? ? ? SRWR WM ? ? ? -1 -1 ? ? ? ? HIGH ? 1 100 _LOCK 5

*CASE aSRWR_LD2_HD1
*SOURCE ? ? ? ? SEWER ? ? ? WM ? ? ? ? ? ? ? ? LOWDEMANDSEWER HIGH ? ?
*TARGET ? ? ? ? ? ? ? SRWR WM ? ? ? -1 -1 ? ? ? ? HIGH 1 ? 100 _LOCK 5

*CASE aSRWR_LD2_HD2
*SOURCE ? ? ? ? SEWER ? ? ? WM ? ? ? ? ? ? ? ? LOWDEMANDSEWER HIGH ? ?
*TARGET ? ? ? ? ? ? ? SRWR WM ? ? ? -1 -1 ? ? ? ? HIGH 1 1 100 _LOCK 5

*CASE aSRWR_HD1_LD1
*SOURCE ? ? ? ? SEWER ? ? ? WM ? ? ? ? ? ? ? ? HIGH LOWDEMANDWATER ? ?
*TARGET ? ? ? ? ? ? ? SRWR WM ? ? ? -1 -1 ? ? ? HIGH ? ? ? 100 _LOCK 5

*CASE aSRWR_HD1_LD2
*SOURCE ? ? ? ? SEWER ? ? ? WM ? ? ? ? ? ? ? ? HIGH LOWDEMANDWATER ? ?
*TARGET ? ? ? ? ? ? ? SRWR WM ? ? ? -1 -1 ? ? ? HIGH ? ? 1 100 _LOCK 5

*CASE aSRWR_HD2_LD1
*SOURCE ? ? ? ? SEWER ? ? ? WM ? ? ? ? ? ? ? ? HIGH LOWDEMANDWATER ? ?

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 *TARGET ? ? ? ? ? ? ? SRWR WM ? ? ? -1 -1 ? ? ? HIGH ? 1 ? 100 _LOCK 5

*CASE aSRWR_HD2_LD2
*SOURCE ? ? ? ? SEWER ? ? ? WM ? ? ? ? ? ? ? ? HIGH LOWDEMANDWATER ? ?
 *TARGET ? ? ? ? ? ? ? SRWR WM ? ? ? -1 -1 ? ? ? HIGH ? 1 1 100 _LOCK 5

;-----------ROADS, WATER, AND SEWER PIPES--------

*CASE aRWS_LD1_LD1
*SOURCE ROADS ? ? ? SEWER ? ? ? WM ? ? ? ? ? ? ? ? LOWDEMANDSEWER
LOWDEMANDWATER ? ?
 *TARGET ? ? ? ? ? ? ? ? WM ? ? RWS -1 -1 ? ? ? ? ? ? ? ? 100 _AGE 1 _LOCK 5

*CASE aRWS_LD1_LD2
*SOURCE ROADS ? ? ? SEWER ? ? ? WM ? ? ? ? ? ? ? ? LOWDEMANDSEWER
LOWDEMANDWATER ? ?
 *TARGET ? ? ? ? ? ? ? ? WM ? ? RWS -1 -1 ? ? ? ? ? ? ? 1 100 _AGE 1 _LOCK 5

*CASE aRWS_LD2_LD1
*SOURCE ROADS ? ? ? SEWER ? ? ? WM ? ? ? ? ? ? ? ? LOWDEMANDSEWER
LOWDEMANDWATER ? ?
 *TARGET ? ? ? ? ? ? ? ? WM ? ? RWS -1 -1 ? ? ? ? ? ? 1 ? 100 _AGE 1 _LOCK 5

*CASE aRWS_LD2_LD2
*SOURCE ROADS ? ? ? SEWER ? ? ? WM ? ? ? ? ? ? ? ? LOWDEMANDSEWER
LOWDEMANDWATER ? ?
 *TARGET ? ? ? ? ? ? ? ? WM ? ? RWS -1 -1 ? ? ? ? ? ? 1 1 100 _AGE 1 _LOCK 5

*CASE aRWS_HD1_HD1
*SOURCE ROADS ? ? ? SEWER ? ? ? WM ? ? ? ? ? ? ? ? HIGH HIGH ? ?
 *TARGET ? ? ? ? ? ? ? ? WM ? ? RWS -1 -1 ? ? ? HIGH HIGH ? ? 100 _AGE 1 _LOCK 5

*CASE aRWS_HD1_HD2
*SOURCE ROADS ? ? ? SEWER ? ? ? WM ? ? ? ? ? ? ? ? HIGH HIGH ? ?
 *TARGET ? ? ? ? ? ? ? ? WM ? ? RWS -1 -1 ? ? ? HIGH HIGH ? 1 100 _AGE 1 _LOCK 5

*CASE aRWS_HD2_HD1
*SOURCE ROADS ? ? ? SEWER ? ? ? WM ? ? ? ? ? ? ? ? HIGH HIGH ? ?
 *TARGET ? ? ? ? ? ? ? ? WM ? ? RWS -1 -1 ? ? ? HIGH HIGH 1 ? 100 _AGE 1 _LOCK 5

*CASE aRWS_HD2_HD2
*SOURCE ROADS ? ? ? SEWER ? ? ? WM ? ? ? ? ? ? ? ? HIGH HIGH ? ?
 *TARGET ? ? ? ? ? ? ? ? WM ? ? RWS -1 -1 ? ? ? HIGH HIGH 1 1 100 _AGE 1 _LOCK 5

*CASE aRWS_LD1_HD1
*SOURCE ROADS ? ? ? SEWER ? ? ? WM ? ? ? ? ? ? ? ? LOWDEMANDSEWER HIGH ? ?
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 *TARGET ? ? ? ? ? ? ? ? WM ? ? RWS -1 -1 ? ? ? ? HIGH ? ? 100 _AGE 1  _LOCK 5

*CASE aRWS_LD1_HD2
*SOURCE ROADS ? ? ? SEWER ? ? ? WM ? ? ? ? ? ? ? ? LOWDEMANDSEWER HIGH ? ?
 *TARGET ? ? ? ? ? ? ? ? WM ? ? RWS -1 -1 ? ? ? ? HIGH ? 1 100 _AGE 1  _LOCK 5

*CASE aRWS_LD2_HD1
*SOURCE ROADS ? ? ? SEWER ? ? ? WM ? ? ? ? ? ? ? ? LOWDEMANDSEWER HIGH ? ?
 *TARGET ? ? ? ? ? ? ? ? WM ? ? RWS -1 -1 ? ? ? ? HIGH 1 ? 100 _AGE 1  _LOCK 5

*CASE aRWS_LD2_HD2
*SOURCE ROADS ? ? ? SEWER ? ? ? WM ? ? ? ? ? ? ? ? LOWDEMANDSEWER HIGH ? ?
 *TARGET ? ? ? ? ? ? ? ? WM ? ? RWS -1 -1 ? ? ? ? HIGH 1 1 100 _AGE 1  _LOCK 5

*CASE aRWS_HD1_LD1
*SOURCE ROADS ? ? ? SEWER ? ? ? WM ? ? ? ? ? ? ? ? HIGH LOWDEMANDWATER ? ?
 *TARGET ? ? ? ? ? ? ? ? WM ? ? RWS -1 -1 ? ? ? HIGH ? ? ? 100 _AGE 1  _LOCK 5

*CASE aRWS_HD1_LD2
*SOURCE ROADS ? ? ? SEWER ? ? ? WM ? ? ? ? ? ? ? ? HIGH LOWDEMANDWATER ? ?
 *TARGET ? ? ? ? ? ? ? ? WM ? ? RWS -1 -1 ? ? ? HIGH ? ? 1 100 _AGE 1  _LOCK 5

*CASE aRWS_HD2_LD1
*SOURCE ROADS ? ? ? SEWER ? ? ? WM ? ? ? ? ? ? ? ? HIGH LOWDEMANDWATER ? ?
 *TARGET ? ? ? ? ? ? ? ? WM ? ? RWS -1 -1 ? ? ? HIGH ? 1 ? 100 _AGE 1  _LOCK 5

*CASE aRWS_HD2_LD2
*SOURCE ROADS ? ? ? SEWER ? ? ? WM ? ? ? ? ? ? ? ? HIGH LOWDEMANDWATER ? ?
 *TARGET ? ? ? ? ? ? ? ? WM ? ? RWS -1 -1 ? ? ? HIGH ? 1 1 100 _AGE 1  _LOCK 5

;-------CASE DEATH------

*CASE _DEATH
*SOURCE  ? ? ? ? ? ? ? ? ? ? ? ? ? ? ? ? ? ? ? ? ? ?
*TARGET  ? ? ? ? ? ? ? ? ? ? ? ? ? ? ? ? ? ? ? ? ? ? 100 _LOCK 1  {regen same as source}



;FOR cl2 := 0 TO 25
;*CASE adeckreplace   _CP (cl2 * 5 + 1)..(cl2 * 5 + 5)
;  *SOURCE bridges allwood ? ? ? ? ? ? ? ?
; *TARGET ? ? ? ? ? ? ? (cl2 * 5 + 1) ? ? 100  _LOCK 5
;ENDFOR
```

8.5.6 *Yields*

;-- DETERIORATION CURVES

;-- Sewer deterioration per material/diameter

```
*Y ? ? ? ? SEWER CONCRETE SMALL ? ? ? ? ? ? ? ? ? ? ? ? ? ? ? ; Condition index for concrete sewer pipes (small diameter)
ytagesewer 0
1
2
3
4
5
6
7
8
9
10
11
12
13
14
15
16
17
18
19
20
21
22
23
24
25
26
27
28
29
30
31
32
33
34
35
36
37
38
```

85
86
87
88
89
90
91
92
93
94
95
96
97
98
99
100
ytreliabilitysewer 0
100
100
100
100
100
100
100
100
100
100
100
100
100
100
100
100
100
100
100
100
100
100
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99
98
98
98
97
97
96
96
95
94
93
92
91
89
88
86
84
81
79
76
73
70
66

63
59
55
50
46
41
37
32
28
24
20
16
13
10
8
6
4
3
2
1
1
0
0
0
0

*Y ? ? ? ? SEWER CONCRETE MOYEN ? ? ? ? ? ? ? ? ? ? ? ? ? ? ? ; Condition index for concrete sewer pipes (moyen diameter)
ytagesewer 0
1
2
3
4
5
6
7
8
9
10
11
12
13
14
15
16
17

64
65
66
67
68
69
70
71
72
73
74
75
76
77
78
79
80
81
82
83
84
85
86
87
88
89
90
91
92
93
94
95
96
97
98
99
100
ytreliabilitysewer 0
100
100
100
100
100
100
100
100

100
100
100
100
100
100
100
100
100
100
100
100
100
100
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100
99
99
99
99
99
99
98
98
98
98
97
97
96
96
95
95
94
94
93
92
91

90
89
88
86
85
84
82
81
79
77
75
73
71
69
66
64
61
59
56
53
51
48
45
42
40
37
34
31
29
26
24
21
19
17
15
13
11
10
8
7
6
5
4
3
3
2

*Y ? ? ? ? SEWER CONCRETE LARGE ? ? ? ? ? ? ? ? ? ? ? ? ? ? ? ; Condition index for concrete sewer pipes (large diameter)
ytagesewer 0
1
2
3
4
5
6
7
8
9
10
11
12
13
14
15
16
17
18
19
20
21
22
23
24
25
26
27
28
29
30
31
32
33
34
35
36
37
38
39
40
41
42

89
90
91
92
93
94
95
96
97
98
99
100
ytreliabilitysewer 0
100
100
100
100
100
100
100
100
100
100
100
100
100
100
100
100
100
100
100
100
100
100
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99
99
98
98
98
97
97
97
96
95
95
94
93
92
91
90
89
87
86
84
82
80
78
76
73

71
68
65
62
58
55
51
48
44
40
37
33
30
26
23
20
17
14
12
9
8

*Y ? ? ? ? SEWER PLASTIC SMALL ? ? ? ? ? ? ? ? ? ? ? ? ? ? ; Condition index for plastic sewer pipes (small diameter)
ytagesewer 0
1
2
3
4
5
6
7
8
9
10
11
12
13
14
15
16
17
18
19
20
21

68
69
70
71
72
73
74
75
76
77
78
79
80
81
82
83
84
85
86
87
88
89
90
91
92
93
94
95
96
97
98
99
100
ytreliabilitysewer 0
100
100
100
100
100
100
100
100
100
100
100
100

100
100
100
100
100
100
100
100
100
100
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100
99
99
99
99
98
98
98
97
97
96
95
94
93
92
91
89
88
86
83
81
78
76
73
69
66
62
58
54
50
45

41
37
33
28
24
21
17
14
11
9
7
5
4
3
2
1
1
1
0
0
0
0
0
0
0
0
0
0
0
0
0
0
0
0
0
0
0
0
0
0
0
0

*Y ? ? ? ? SEWER PLASTIC MOYEN ? ? ? ? ? ? ? ? ? ? ? ? ? ? ? ; Condition index for plastic sewer pipes (moyen diameter)
ytagesewer 0

93
94
95
96
97
98
99
100
ytreliabilitysewer 0
100
100
100
100
100
100
100
100
100
100
100
100
100
100
100
100
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99
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99
98
98
98
97
97
96
95
94
93
92
91
89
87
85
83
81
78
75
72
68
64
60
55
51
46
42
37
32
28
23
19
16
12
9
7
5
4
2
2
1

1
0
0
0
0
0
0
0
0
0
0
0
0
0
0
0
0

*Y ? ? ? ? SEWER PLASTIC LARGE ? ? ? ? ? ? ? ? ? ? ? ? ? ? ? ; Condition index for plastic sewer pipes (large diameter)
ytagesewer 0
1
2
3
4
5
6
7
8
9
10
11
12
13
14
15
16
17
18
19
20
21
22
23
24
25

72
73
74
75
76
77
78
79
80
81
82
83
84
85
86
87
88
89
90
91
92
93
94
95
96
97
98
99
100
ytreliabilitysewer 0
100
100
100
100
100
100
100
100
100
100
100
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100

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98
98
98
97
97
96
96
95
94
94
93
92
90
89
88

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86
85
83
81
79
76
74
71
68
65
62
59
55
52
48
44
40
37
33
30
26
23
20
17
14
12
10
8
6
5
4
3
2
1
1
1
0
0

*YC ? ? ? ? ? ? ? ? ? ? ? ? ? ? ? ? ? ? ? ? ? ? ?  ; Condition Index Calculation using the shift function
yreliabilitySR _SHIFT(ytreliabilitysewer, _TH13)
AGESEWER _SHIFT(ytagesewer, _TH13)

;-- Water deterioration per material/diameter
```

*Y ? ? ? ? ? ? ? ? WM IRON SMALL ? ? ? ? ? ? ? ? ? ? ? ; Condition index for iron water pipes (small diameter)
ytagewater 0
1
2
3
4
5
6
7
8
9
10
11
12
13
14
15
16
17
18
19
20
21
22
23
24
25
26
27
28
29
30
31
32
33
34
35
36
37
38
39
40
41
42
43

90
91
92
93
94
95
96
97
98
99
100
ytreliabilitywater 0
100
100
100
100
100
100
100
100
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100
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99
99
99
99
99
98
98
97
97
96
95
94
93
92
91
89
87
84
82
79
75
72
68
63
58
53
48
42
37

31
26
21
17
13
9
6
4
3
2
1
0
0
0
0
0
0
0
0
0

*Y ? ? ? ? ? ? ? ? WM IRON MOYEN ? ? ? ? ? ? ? ? ? ? ? ; Condition index for iron water pipes (moyen diameter)
ytagewater 0
1
2
3
4
5
6
7
8
9
10
11
12
13
14
15
16
17
18
19
20
21
22

69
70
71
72
73
74
75
76
77
78
79
80
81
82
83
84
85
86
87
88
89
90
91
92
93
94
95
96
97
98
99
100
ytreliabilitywater 0
100
100
100
100
100
100
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97
96
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93
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89
87
86
84
81
79
76
73
70
66
63
59
55
50
46
41
37
32
28
24
20
16
13
10
8
6
4

*Y ? ? ? ? ? ? ? ? WM CONCRETE SMALL ? ? ? ? ? ? ? ? ? ? ; Condition index for concrete water pipes (small diameter)
ytagewater 0
1

94
95
96
97
98
99
100
ytreliabilitywater 0
100
100
100
100
100
100
100
100
100
100
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98
97
97
96
95
94
93
92
91
90
88
86
85
82
80
78
75
72
68
65
61
58
54
49
45
41
37
33
29
25
21
18
15
12
9
7
5
4
3
2
1

1
1
0
0
0
0
0
0
0
0
0
0
0
0
0
0
*Y ? ? ? ? ? ? ? ? WM CONCRETE MOYEN ? ? ? ? ? ? ? ? ? ? ; Condition index for concrete water pipes (moyen diameter)
ytagewater 0
1
2
3
4
5
6
7
8
9
10
11
12
13
14
15
16
17
18
19
20
21
22
23
24
25
26
27

74
75
76
77
78
79
80
81
82
83
84
85
86
87
88
89
90
91
92
93
94
95
96
97
98
99
100
ytreliabilitywater 0
100
100
100
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93
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90
89
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86
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83
81

79
77
75
73
70
68
65
62
59
56
53
50
47
43
40
37
34
30
27
24
22
19
17
14
12
10
9
7
6
5
4
3
2
2
1
1

*Y ? ? ? ? ? ? ? ? WM PLASTIC SMALL ? ? ? ? ? ? ? ? ? ? ; Condition index for plastic water pipes (small diameter)
ytagewater 0
1
2
3
4
5
6

99
100
ytreliabilitywater 0
100
100
100
100
100
100
100
100
100
100
100
100
100
100
100
100
100
100
100
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100
99
99
99
99
99
98
98
97
97
96
95
94
93

92
90
89
87
85
82
79
76
73
69
65
61
56
52
47
42
37
32
27
23
19
15
12
9
7
5
3
2
1
1
0
0
0
0
0
0
0
0
0
0
0
0
0
0
0
0

0
0
0
0
0
0
0
0
0
0
0

*Y ? ? ? ? ? ? ? ? WM PLASTIC MOYEN ? ? ? ? ? ? ? ? ? ? ; Condition index for plastic water pipes (moyen diameter)
ytagewater 0
1
2
3
4
5
6
7
8
9
10
11
12
13
14
15
16
17
18
19
20
21
22
23
24
25
26
27
28
29
30
31

78
79
80
81
82
83
84
85
86
87
88
89
90
91
92
93
94
95
96
97
98
99
100
ytreliabilitywater 0
100
100
100
100
100
100
100
100
100
100
100
100
100
100
100
100
100
100
100
100
100
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90
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87
86
85
83
81
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76
74
72
70
68
65
63
61
58
55
53
50
47
45
42

39
37
34
32
29
27
24
22
20
18
16
14
13
11
10
8
7
6
5
4
4
3
2
2
2
1
1
1
1
0
0
0

*YC ? ; Condition Index Calculation using the shift function
yreliabilityWR _SHIFT(ytreliabilitywater, _TH14)
AGEWATER _SHIFT(ytagewater, _TH14)

;-- Road deterioration per type, structure, and traffic intensity

*Y GRAVEL ? ; Condition index for gravel roads with weak structure and light/medium traffic
_AGE ytPCIRoads
0 100
1 100
2 100
3 100

4	99
5	99
6	97
7	95
8	92
9	88
10	82
11	75
12	66
13	57
14	47
15	37
16	27
17	19
18	13
19	8
20	4
21	2
22	1
23	0
24	0
25	0
26	0
27	0
28	0
29	0
30	0
31	0
32	0
33	0
34	0
35	0
36	0
37	0
38	0
39	0
40	0

*Y ROAD WEAK LOCAL ? ; Condition index for asphalt roads with weak structure and light/medium traffic

_AGE	ytPCIRoads
0	100
1	100
2	100
3	100
4	100

5	100
6	100
7	99
8	99
9	98
10	97
11	95
12	93
13	89
14	85
15	79
16	72
17	64
18	55
19	46
20	37
21	28
22	20
23	13
24	8
25	5
26	2
27	1
28	0
29	0
30	0
31	0
32	0
33	0
34	0
35	0
36	0
37	0
38	0
39	0
40	0

*Y ROAD STRONG LOCAL ? ; Condition index for asphalt roads with strong structure and light/medium traffic

_AGE	ytPCIRoads
0	100
1	100
2	100
3	100
4	100
5	100

6	100
7	100
8	100
9	100
10	100
11	100
12	99
13	99
14	98
15	97
16	96
17	93
18	90
19	86
20	81
21	74
22	66
23	57
24	47
25	37
26	27
27	18
28	11
29	6
30	3
31	1
32	0
33	0
34	0
35	0
36	0
37	0
38	0
39	0
40	0

*Y ROADS STRONG COLLECTOR ? ? ? ? ? ? ? ? ? ? ? ? ? ? ? ? ? ? ? ; Condition index for asphalt roads with strong structure and light/medium traffic

_AGE	ytPCIRoads
0	100
1	100
2	100
3	100
4	100
5	100
6	100

7	100
8	100
9	100
10	100
11	100
12	99
13	99
14	98
15	97
16	96
17	93
18	90
19	86
20	81
21	74
22	66
23	57
24	47
25	37
26	27
27	18
28	11
29	6
30	3
31	1
32	0
33	0
34	0
35	0
36	0
37	0
38	0
39	0
40	0

;-- DEMAND CAPACITY FOR SEWER PIPES

*Y ? ? ? ? SEWER ? ? ? ? ? ? ? ? ? ? ? ? LOW ? ? ?

ytagesewercapacity 0

1

3

4

88

89

90

Ytcapsewer 0

1.2526

3.7578

5.0104

6.263

8.7682

10.0208

12.526

13.7786

15.0312

16.2838

18.789

20.0416

22.5468

26.3046

27.5572

28.8098

31.315

33.8202

35.0728

36.3254

37.578

38.8306

40.0832

41.3358

42.5884

43.841

45.0936

46.3462

47.5988

48.8514

50.104

51.3566

52.6092

53.8618

55.1144

56.367

57.6196

58.8722

60.1248

61.3774

62.63

63.8826

65.1352

66.3878

67.6404

68.893

70.1456

71.3982

72.6508

73.9034

75.156

76.4086

77.6612

78.9138

80.1664

81.419

82.6716

83.9242

85.1768

86.4294

87.682

88.9346

90.1872

91.4398

92.6924

93.945

95.1976

96.4502

97.7028

98.9554

100.28

101.46

102.71

103.97

105.22

106.47

107.72

108.97

110.23

111.48

112.73

*Y ? ? ? ? SEWER ? ? ? ? ? ? ? ? ? ? ? ? MEDIUM ? ? ?

ytagesewercapacity 0

1

3

4

5

7

8

10

11

12

13

15

16

18

48

49

50

51

52

53

54

55

56

57

58

59

60

Ytcapsewer 0

2.11

6.33

8.44

10.55

14.77

16.88

21.1

23.21

25.32

27.43

31.65

33.76

37.98

44.31

46.42

48.53

52.75

56.97

59.08

61.19

63.3

65.41

67.52

69.63

71.74

73.85

75.96

78.07

80.18

82.29

84.4

86.51

88.62

90.73

92.84

94.95

97.06

99.17

101.28

103.39

105.5

107.61

109.72

111.83

113.94

116.05

118.16

120.27

122.38

124.49

126.6

*Y ? ? ? ? SEWER ? ? ? ? ? ? ? ? ? ? ? ? ? HIGH ? ? ?

ytagesewercapacity 0

1

3

4

5

7

8

10

11

12

13

15

16

18

21

22

23

25

27

28

29

30

31

32

33

34

35

36

37

38

39

40

Ytcapsewer 0

2.84

8.52

11.36

14.2

19.88

22.72

28.4

31.24

34.08

36.92

42.6

45.44

51.12

59.64

62.48

65.32

71

76.68

79.52

82.36

85.2

88.04

90.88

93.72

96.56

99.4

102.24

105.08

107.92

110.76

113.6

*YC ? ; Condition Index Calculation using the shift function

Ycapsewer _SHIFT(ytcapsewer, _TH20)

AGESEWERCAP _SHIFT(ytagesewercapacity, _TH20)

;-- DEMAND CAPACITY FOR WATER PIPES

*Y ? ? ? ? ? ? ? ? WM ? ? ? ? ? ? ? ? ? LOW ? ?

ytagewatercapacity 0

1

3

4

5

7

8

10

11

12

13

15

16

18

73

74

75

76

77

78

79

80

81

82

83

84

85

86

87

88

89

90

Ytcapwater 0

0.87682

2.63046

3.50728

4.3841

6.13774

7.01456

8.7682

9.64502

10.52184

11.39866

13.1523

14.02912

15.78276

18.41322

19.29004

20.16686

21.9205

23.67414

24.55096

25.42778

26.3046

27.18142

28.05824

28.93506

29.81188

30.6887

31.56552

32.44234

33.31916

34.19598

35.0728

35.94962

36.82644

37.70326

38.58008

39.4569

40.33372

41.21054

42.08736

42.96418

43.841

44.71782

45.59464

46.47146

47.34828

48.2251

49.10192

49.97874

50.85556

51.73238

52.6092

53.48602

54.36284

55.23966

56.11648

56.9933

57.87012

58.74694

59.62376

60.50058

61.3774

62.25422

63.13104

64.00786

64.88468

65.7615

66.63832

67.51514

68.39196

69.26878

70.196

71.022

71.897

72.779

73.654

74.529

75.404

76.279

77.161

78.036

78.911

*Y ? ? ? ? ? ? ? ? ? WM ? ? ? ? ? ? ? ? ? ? MEDIUM ? ?

ytagewatercapacity 0

1

3

4

5

7

8

10

11

12

13

15

16

18

21

22

23

25

27

28

29

30

31

32

58

59

60

Ytcapwater 0

1.477

4.431

5.908

7.385

10.339

11.816

14.77

16.247

17.724

19.201

22.155

23.632

26.586

31.017

32.494

33.971

36.925

39.879

41.356

42.833

44.31

45.787

47.264

48.741

50.218

51.695

53.172

54.649

56.126

57.603

59.08

60.557

62.034

63.511

64.988

66.465

67.942

69.419

70.896

72.373

73.85

75.327

76.804

78.281

79.758

81.235

82.712

84.189

85.666

87.143

88.62

*Y ? ? ? ? ? ? ? ? WM ? ? ? ? ? ? ? ? ? HIGH ? ?

ytagewatercapacity 0

1

3

4

5

7

8

10

11

12

13

15

16

18

21

22

23

25

27

28

29

30

31

32

33

34

35

36

37

38

39

40

Ytcapwater 0

1.988

5.964

7.952

9.94

13.916

15.904

19.88

21.868

23.856

25.844

29.82

31.808

35.784

41.748

43.736

45.724

49.7

53.676

55.664

57.652

59.64

61.628

63.616

65.604

67.592

69.58

71.568

73.556

75.544

77.532

79.52

*YC ? ; Condition Index Calculation using the shift function

Ycapwater _SHIFT(ytcapwater, _TH21)

AGEWATERCAP _SHIFT(ytagewatercapacity, _TH21)

;-- ROADS' INTERVENTIONS IMPACTS COST - CONDITION IMPROVEMENT - TIME - SPACE - RISK ==> Will be calculated in output per traffic distribution and reliability inverse (probability of failure)

*Y ROADS ? LOCAL ? ? ? ? ? ? ? ? ? ? ? ? ? ? ? ? ? ? ?   ; direct and indirect costs for roads interventions (Per m2)

_AGE yCS$ yMS$ YRS$ YPA$ YRC$

0   0   0   0   0   0

1 0.36   4   28   46   72

40 0.79 8.83 61.83 101.57 158.99

*Y ROADS ? LOCAL ? ? ? ? ? ? ? ? ? ? ? ? ? ? ? ? ? ? ? ; direct and indirect time for roads interventions (Per m2)

_AGE yCSL yMSL YRSL YPAL YRCL

0   0   0   0   0   0

1 0.25   2   5   8   12

40 0.25   2   5   8   12

*Y ROADS ? COLLECTOR ? ? ? ? ? ? ? ? ? ? ? ? ? ? ? ? ? ? ?   ; direct and indirect costs for roads interventions (Per m2)

_AGE yCS$ yMS$ YRS$ YPA$ YRC$

0   0   0   0   0   0

1 0.75   8   60   90   145

40 1.66 17.66 132.48 198.72 320.17

*Y ROADS ? COLLECTOR ? ? ? ? ? ? ? ? ? ? ? ? ? ? ? ? ? ? ?   ; direct and indirect time for roads interventions (Per m2)

_AGE yCSL yMSL YRSL YPAL YRCL

0   0   0   0   0   0

1 0.5   4   9   15   25

40 0.5   4   9   15   25

*Y ROADS ?   ; direct and indirect space for roads interventions (% utilization per m2)

_AGE yCS! yMS! YRS! YPA! YRC!

0 0 0 0 0 0

1 0.1 0.2 1 0.3 1

40 0.1 0.2 1 0.3 1

;-- SEWER PIPES' INTERVENTIONS IMPACTS COST - CONDITION IMPROVEMENT - TIME - SPACE - RISK ==> Will be calculated in output per traffic distribution and reliability inverse (probability of failure)

*Y ? ? ? ? SEWER CONCRETE SMALL ? ? ? ? ? ? ? ? ? ? LOWDEMANDSEWER ? ? ?

_AGE yreplacesewer-LD1$ yreplacesewer-LD2$

0 0 0

1 620.5 1307

50 1670 3519

*Y ? ? ? ? SEWER CONCRETE MOYEN ? ? ? ? ? ? ? ? ? ? LOWDEMANDSEWER ? ? ?

_AGE yreplacesewer-LD1$ yreplacesewer-LD2$

0 0 0

1 1307 3121

50 3519 8399

*Y ? ? ? ? SEWER CONCRETE LARGE ? ? ? ? ? ? ? ? ? ? LOWDEMANDSEWER ? ? ?

_AGE yreplacesewer-LD1$ yreplacesewer-LD2$

0 0 0

1 3121 3750

50 8399 10093

*Y ? ? ? ? SEWER CONCRETE SMALL ? ? ? ? ? ? ? ? ? ? HIGH ? ? ?

_AGE yreplacesewer-HD1$ yreplacesewer-HD2$

0 0 0

1 620.5 1307

50 1670 3519

*Y ? ? ? ? SEWER CONCRETE MOYEN ? ? ? ? ? ? ? ? ? ? HIGH ? ? ?

_AGE yreplacesewer-HD1$ yreplacesewer-HD2$

0	0	0
1	1307	3121
50	3519	8399

*Y ? ? ? ? SEWER CONCRETE LARGE ? ? ? ? ? ? ? ? ? ? HIGH ? ? ?

_AGE yreplacesewer-HD1$ yreplacesewer-HD2$

0	0	0
1	3121	3750
50	8399	10093

*Y ? ? ? ? SEWER PLASTIC SMALL ? ? ? ? ? ? ? ? ? ? LOWDEMANDSEWER ? ? ?

_AGE ylinersewer-LD1$ ylinersewer-LD2$

0	0	0
1	434.5	915.2
50	1169	2463

*Y ? ? ? ? SEWER PLASTIC MOYEN ? ? ? ? ? ? ? ? ? ? LOWDEMANDSEWER ? ? ?

_AGE ylinersewer-LD1$ ylinersewer-LD2$

0	0	0
1	915.2	2184
50	2463	5880

*Y ? ? ? ? SEWER PLASTIC LARGE ? ? ? ? ? ? ? ? ? ? LOWDEMANDSEWER ? ? ?

_AGE ylinersewer-LD1$ ylinersewer-LD2$

0	0	0
1	2184	2621
50	5880	7056

*Y ? ? ? ? SEWER PLASTIC SMALL ? ? ? ? ? ? ? ? ? ? HIGH ? ? ?

_AGE ylinersewer-HD1$ ylinersewer-HD2$

0 0 0

1 434.5 915.2

50 1169 2463

*Y ? ? ? ? SEWER PLASTIC MOYEN ? ? ? ? ? ? ? ? ? ? HIGH ? ? ?

_AGE ylinersewer-HD1$ ylinersewer-HD2$

0 0 0

1 915.2 2184

50 2463 5880

*Y ? ? ? ? SEWER PLASTIC LARGE ? ? ? ? ? ? ? ? ? ? HIGH ? ? ?

_AGE ylinersewer-HD1$ ylinersewer-HD2$

0 0 0

1 2184 2621

50 5880 7056

*Y ? ? ? ? SEWER ? ? ? ? ? ? ? ? ? ? ? ? ? ? ? ?

_AGE ylinersewer-LD1! ylinersewer-LD2! ylinersewer-HD1! ylinersewer-HD2! yreplacesewer-LD1! yreplacesewer-LD2! yreplacesewer-HD1! yreplacesewer-HD2!

0 0 0 0 0 0 0 0
0

1 1 1 1 1 1 1 1
1

50 1 1 1 1 1 1 1
1

*Y ? ? ? ? SEWER ? SMALL ? ? ? ? ? ? ? ? ? ? ? ? ? ?

_AGE ylinersewer-LD1L ylinersewer-LD2L ylinersewer-HD1L ylinersewer-HD2L yreplacesewer-LD1L yreplacesewer-LD2L yreplacesewer-HD1L yreplacesewer-HD2L

0 0 0 0 0 0 0 0
0

1 1.5 2 1.5 2 2.5 3 2.5
3

50 1.5 2 1.5 2 2.5 3 2.5
3

*Y ? ? ? ? SEWER ? MOYEN ? ? ? ? ? ? ? ? ? ? ? ? ? ?

_AGE ylinersewer-LD1L ylinersewer-LD2L ylinersewer-HD1L ylinersewer-HD2L
yreplacesewer-LD1L yreplacesewer-LD2L yreplacesewer-HD1L yreplacesewer-HD2L

0 0 0 0 0 0 0 0
0

1 2 2.5 2 2.5 3 3.5 3
3.5

50 2 2.5 2 2.5 3 3.5 3
3.5

*Y ? ? ? ? SEWER ? LARGE ? ? ? ? ? ? ? ? ? ? ? ? ? ?

_AGE ylinersewer-LD1L ylinersewer-LD2L ylinersewer-HD1L ylinersewer-HD2L
yreplacesewer-LD1L yreplacesewer-LD2L yreplacesewer-HD1L yreplacesewer-HD2L

0 0 0 0 0 0 0 0
0

1 2.5 3 2.5 3 3.5 4 3.5
4

50 2.5 3 2.5 3 3.5 4 3.5
4

;-- WATER PIPES' INTERVENTIONS IMPACTS COST - CONDITION IMPROVEMENT - TIME - SPACE - RISK ==> Will be calculated in output per traffic distribution and reliability inverse (probability of failure)

*Y ? ? ? ? ? ? ? ? WM CONCRETE SMALL ? ? ? ? ? ? ? LOWDEMANDWATER ? ?

_AGE yreplacewater-LD1$ yreplacewater-LD2$

0 0 0

1 496.4 1046

50 1336 2815

*Y ? ? ? ? ? ? ? ? WM CONCRETE MOYEN ? ? ? ? ? ? ? LOWDEMANDWATER ? ?

_AGE yreplacewater-LD1$ yreplacewater-LD2$

0 0 0

1 1046 2815

50 2496.5 6719.6

*Y ? ? ? ? ? ? ? ? WM PLASTIC SMALL ? ? ? ? ? ? ? LOWDEMANDWATER ? ?

_AGE ylinerwater-LD1$ ylinerwater-LD2$

0 0 0

1 347.5 732.2

50 935.3 1971

*Y ? ? ? ? ? ? ? ? WM PLASTIC MOYEN ? ? ? ? ? ? ? LOWDEMANDWATER ? ?

_AGE ylinerwater-LD1$ ylinerwater-LD2$

0 0 0

1 732.2 1747.6

50 1971 4703.7

*Y ? ? ? ? ? ? ? ? WM PLASTIC SMALL ? ? ? ? ? ? ? HIGH ? ?

_AGE ylinerwater-HD1$ ylinerwater-HD2$

0 0 0

1 347.5 732.2

50 935.3 1971

*Y ? ? ? ? ? ? ? ? WM PLASTIC MOYEN ? ? ? ? ? ? ? HIGH ? ?

_AGE ylinerwater-HD1$ ylinerwater-HD2$

0 0 0

1 732.2 1747.6

50 1971 4703.7

*Y ? ? ? ? ? ? ? ? WM CONCRETE MOYEN ? ? ? ? ? ? ? HIGH ? ?

_AGE yreplacewater-HD1$ yreplacewater-HD2$

0 0 0

1 1046 2815

50 2496.5 6719.6

*Y ? ? ? ? ? ? ? ? WM IRON SMALL ? ? ? ? ? ? ? HIGH ? ?

_AGE yreplacewater-HD1$ yreplacewater-HD2$

0 0 0

1 496.4 1046

50 1336 2815

*Y ? ? ? ? ? ? ? ? WM IRON MOYEN ? ? ? ? ? ? ? HIGH ? ?

_AGE yreplacewater-HD1$ yreplacewater-HD2$

0 0 0

1 1046 2815

50 2496.5 6719.6

*Y ? ? ? ? ? ? ? ? WM IRON SMALL ? ? ? ? ? ? ? LOWDEMANDWATER ? ?

_AGE yreplacewater-LD1$ yreplacewater-LD2$

0 0 0

1 496.4 1046

50 1336 2815

*Y ? ? ? ? ? ? ? ? WM IRON MOYEN ? ? ? ? ? ? ? LOWDEMANDWATER ? ?

_AGE yreplacewater-LD1$ yreplacewater-LD2$

0 0 0

1 1046 2815

50 2496.5 6719.6

*Y ? ? ? ? ? ? ? ? WM ? ? ? ? ? ? ? ? ? ? ? ?

_AGE ylinerwater-LD1! ylinerwater-LD2! ylinerwater-HD1! ylinerwater-HD2! yreplacewater-LD1! yreplacewater-LD2! yreplacewater-HD1! yreplacewater-HD2!

0 0 0 0 0 0 0 0 0

1 1 1 1 1 1 1 1 1

50 1 1 1 1 1 1 1 1

*Y ? ? ? ? ? ? ? ? WM ? SMALL ? ? ? ? ? ? ? ? ? ?

_AGE yreplacewater-LD1L yreplacewater-LD2L yreplacewater-HD1L yreplacewater-HD2L ylinerwater-LD1L ylinerwater-LD2L ylinerwater-HD1L ylinerwater-HD2L

0 0 0 0 0 0 0 0 0

1 2.5 3 2.5 3 1.5 2 1.5 2

50 2.5 3 2.5 3 1.5 2 1.5 2

*Y ? ? ? ? ? ? ? ? WM ? MOYEN ? ? ? ? ? ? ? ? ? ?

_AGE yreplacewater-LD1L yreplacewater-LD2L yreplacewater-HD1L yreplacewater-HD2L ylinerwater-LD1L ylinerwater-LD2L ylinerwater-HD1L ylinerwater-HD2L

0 0 0 0 0 0 0 0 0

1 3 3.5 3 3.5 2 2.5 2.5 2.5

50 3 3.5 3 3.5 2 2.5 2.5 2.5

;-- ROADS AND SEWER PIPES' INTERVENTIONS IMPACTS COST - CONDITION IMPROVEMENT - TIME - SPACE - RISK ==> Will be calculated in output per traffic distribution and reliability inverse (probability of failure)

*Y ROADS ? ? ? SEWER ? SMALL ? ? ? ? ? ? ? ? ? ? LOWDEMANDSEWER ? ? ?

_AGE yRDSR-LD1$ yRDSR-LD2$

0	0	0
1	650.5	1337
50	1751	3600

*Y ROADS ? ? ? SEWER ? SMALL ? ? ? ? ? ? ? ? ? ? HIGH ? ? ?

_AGE yRDSR-HD1$ yRDSR-HD2$

0	0	0
1	650.5	1337
50	1751	3600

*Y ROADS ? ? ? SEWER ? MOYEN ? ? ? ? ? ? ? ? ? ? LOWDEMANDSEWER ? ? ?

_AGE yRDSR-LD1$ yRDSR-LD2$

0	0	0
1	1337	3151
50	3600	8480

*Y ROADS ? ? ? SEWER ? MOYEN ? ? ? ? ? ? ? ? ? ? HIGH ? ? ?

_AGE yRDSR-HD1$ yRDSR-HD2$

0	0	0
1	1337	3151
50	3600	8480

*Y ROADS ? ? ? SEWER ? LARGE ? ? ? ? ? ? ? ? ? ? LOWDEMANDSEWER ? ? ?

_AGE yRDSR-LD1$ yRDSR-LD2$

0	0	0
1	3151	3780
50	8480	10174

*Y ROADS ? ? ? SEWER ? LARGE ? ? ? ? ? ? ? ? ? ? HIGH ? ? ?

_AGE yRDSR-HD1$ yRDSR-HD2$

0	0	0
1	3151	3780
50	8480	10174

*Y ROADS ? ? ? SEWER ? ? ? ? ? ? ? ? ? ? ? ? ? ? ? ? ?

_AGE yRDSR-LD1! yRDSR-LD2! yRDSR-HD1! yRDSR-HD2!

0	0	0	0	0
1	1	1	1	1
50	1	1	1	1

*Y ROADS ? ? ? SEWER ? SMALL ? ? ? ? ? ? ? ? ? ? ? ? ? ?

_AGE yRDSR-LD1L yRDSR-LD2L yRDSR-HD1L yRDSR-HD2L

0	0	0	0	0
1	4	4.5	4	4.5
50	4	4.5	4	4.5

*Y ROADS ? ? ? SEWER ? MOYEN ? ? ? ? ? ? ? ? ? ? ? ? ? ?

_AGE yRDSR-LD1L yRDSR-LD2L yRDSR-HD1L yRDSR-HD2L

0	0	0	0	0
1	4.5	5	4.5	5
50	4.5	5	4.5	5

*Y ROADS ? ? ? SEWER ? LARGE ? ? ? ? ? ? ? ? ? ? ? ? ? ?

_AGE yRDSR-LD1L yRDSR-LD2L yRDSR-HD1L yRDSR-HD2L

0	0	0	0	0
1	5	5.5	5	5.5
50	5	5.5	5	5.5

;-- ROADS AND WATER PIPES' INTERVENTIONS IMPACTS COST - CONDITION IMPROVEMENT - TIME - SPACE - RISK ==> Will be calculated in output per traffic distribution and reliability inverse (probability of failure)

*Y ROADS ? ? ? ? ? ? ? WM ? SMALL ? ? ? ? ? ? ? LOWDEMANDWATER ? ?

_AGE yRDWR-LD1$ yRDWR-LD2$

0 0 0

1 526.4 1076

50 1417 2896

*Y ROADS ? ? ? ? ? ? ? WM ? SMALL ? ? ? ? ? ? ? HIGH ? ?

_AGE yRDWR-HD1$ yRDWR-HD2$

0 0 0

1 526.4 1076

50 1417 2896

*Y ROADS ? ? ? ? ? ? ? WM ? MOYEN ? ? ? ? ? ? ? LOWDEMANDWATER ? ?

_AGE yRDWR-LD1$ yRDWR-LD2$

0 0 0

1 1076 2526.5

50 2896 6800.3

*Y ROADS ? ? ? ? ? ? ? WM ? MOYEN ? ? ? ? ? ? ? HIGH ? ?

_AGE yRDWR-HD1$ yRDWR-HD2$

0 0 0

1 1076 2526.5

50 2896 6800.3

*Y ROADS ? ? ? ? ? ? ? WM ? ? ? ? ? ? ? ? ? ? ? ? ?

_AGE yRDWR-LD1! yRDWR-LD2! yRDWR-HD1! yRDWR-HD2!

0 0 0 0 0

1	1	1	1	1
50	1	1	1	1

*Y ROADS ? ? ? ? ? ? ? WM ? SMALL ? ? ? ? ? ? ? ? ? ?

_AGE	yRDWR-LD1L	yRDWR-LD2L	yRDWR-HD1L	yRDWR-HD2L
0	0	0	0	0
1	3	3.5	3.5	3.5
50	3	3.5	3.5	3.5

*Y ROADS ? ? ? ? ? ? ? WM ? MOYEN ? ? ? ? ? ? ? ? ? ?

_AGE	yRDWR-LD1L	yRDWR-LD2L	yRDWR-HD1L	yRDWR-HD2L
0	0	0	0	0
1	3.5	4	3.5	4
50	3.5	4	3.5	4

;-- WATER AND SEWER PIPES' INTERVENTIONS IMPACTS COST - CONDITION IMPROVEMENT - TIME - SPACE - RISK ==> Will be calculated in output per traffic distribution and reliability inverse (probability of failure)

*Y ? ? ? ? SEWER ? SMALL ? WM ? SMALL ? ? ? ? ? ? LOWDEMANDSEWER LOWDEMANDWATER ? ?

_AGE	ySRWR-LD1-LD1$	ySRWR-LD1-LD2$	ySRWR-LD2-LD1$	ySRWR-LD2-LD2$
0	0	0	0	0
1	873.73	1249.88	1352.91	1765.05
50	2254.84	3364.15	3641.48	4750.8

*Y ? ? ? ? SEWER ? SMALL ? WM ? MOYEN ? ? ? ? ? ? LOWDEMANDSEWER LOWDEMANDWATER ? ?

_AGE	ySRWR-LD1-LD1$	ySRWR-LD1-LD2$	ySRWR-LD2-LD1$	ySRWR-LD2-LD2$
0	0	0	0	0
1	1249.88	2337.8	1765.05	2852.97
50	3664.15	6292.39	4750.8	7650.8

*Y ? ? ? ? SEWER ? MOYEN ? WM ? SMALL ? ? ? ? ? ? LOWDEMANDSEWER LOWDEMANDWATER ? ?

_AGE	ySRWR-LD1-LD1$	ySRWR-LD1-LD2$	ySRWR-LD2-LD1$	ySRWR-LD2-LD2$
0	0	0	0	0
1	1352.91	1765.05	2712.81	3124.95
50	3641.48	4750.8	7301.77	8411.09

*Y ? ? ? ? SEWER ? MOYEN ? WM ? MOYEN ? ? ? ? ? ? LOWDEMANDSEWER LOWDEMANDWATER ? ?

_AGE	ySRWR-LD1-LD1$	ySRWR-LD1-LD2$	ySRWR-LD2-LD1$	ySRWR-LD2-LD2$
0	0	0	0	0
1	1765.05	2852.97	3124.95	4212.87
50	4750.8	7679.03	8411.09	11339.32

*Y ? ? ? ? SEWER ? LARGE ? WM ? SMALL ? ? ? ? ? ? LOWDEMANDSEWER LOWDEMANDWATER ? ?

_AGE	ySRWR-LD1-LD1$	ySRWR-LD1-LD2$	ySRWR-LD2-LD1$	ySRWR-LD2-LD2$
0	0	0	0	0
1	2712.81	3124.95	3184.83	3596.97
50	7301.77	8411.09	8572.24	9681.56

*Y ? ? ? ? SEWER ? LARGE ? WM ? MOYEN ? ? ? ? ? ? LOWDEMANDSEWER LOWDEMANDWATER ? ?

_AGE	ySRWR-LD1-LD1$	ySRWR-LD1-LD2$	ySRWR-LD2-LD1$	ySRWR-LD2-LD2$
0	0	0	0	0
1	3124.95	4212.87	3596.97	4684.89
50	8411.09	11339.32	9681.56	12609.79

*Y ? ? ? ? SEWER ? SMALL ? WM ? SMALL ? ? ? ? ? ? LOWDEMANDSEWER HIGH ? ?

_AGE	ySRWR-LD1-HD1$	ySRWR-LD1-HD2$	ySRWR-LD2-HD1$	ySRWR-LD2-HD2$
0	0	0	0	0

1 873.73 1249.88 1352.91 1765.05

50 2254.84 3364.15 3641.48 4750.8

*Y ? ? ? ? SEWER ? SMALL ? WM ? MOYEN ? ? ? ? ? ? LOWDEMANDSEWER HIGH ? ?

_AGE ySRWR-LD1-HD1$ ySRWR-LD1-HD2$ ySRWR-LD2-HD1$ ySRWR-LD2-HD2$

0 0 0 0 0

1 1249.88 2337.8 1765.05 2852.97

50 3664.15 6292.39 4750.8 7650.8

*Y ? ? ? ? SEWER ? MOYEN ? WM ? SMALL ? ? ? ? ? ? LOWDEMANDSEWER HIGH ? ?

_AGE ySRWR-LD1-HD1$ ySRWR-LD1-HD2$ ySRWR-LD2-HD1$ ySRWR-LD2-HD2$

0 0 0 0 0

1 1352.91 1765.05 2712.81 3124.95

50 3641.48 4750.8 7301.77 8411.09

*Y ? ? ? ? SEWER ? MOYEN ? WM ? MOYEN ? ? ? ? ? ? LOWDEMANDSEWER HIGH ? ?

_AGE ySRWR-LD1-HD1$ ySRWR-LD1-HD2$ ySRWR-LD2-HD1$ ySRWR-LD2-HD2$

0 0 0 0 0

1 1765.05 2852.97 3124.95 4212.87

50 4750.8 7679.03 8411.09 11339.32

*Y ? ? ? ? SEWER ? LARGE ? WM ? SMALL ? ? ? ? ? ? LOWDEMANDSEWER HIGH ? ?

_AGE ySRWR-LD1-HD1$ ySRWR-LD1-HD2$ ySRWR-LD2-HD1$ ySRWR-LD2-HD2$

0 0 0 0 0

1 2712.81 3124.95 3184.83 3596.97

50 7301.77 8411.09 8572.24 9681.56

*Y ? ? ? ? SEWER ? LARGE ? WM ? MOYEN ? ? ? ? ? ? LOWDEMANDSEWER HIGH ? ?

_AGE ySRWR-LD1-HD1$ ySRWR-LD1-HD2$ ySRWR-LD2-HD1$ ySRWR-LD2-HD2$

0 0 0 0 0

1 3124.95 4212.87 3596.97 4684.89

50 8411.09 11339.32 9681.56 12609.79

*Y ? ? ? ? SEWER ? SMALL ? WM ? SMALL ? ? ? ? ? ? HIGH LOWDEMANDWATER ? ?

_AGE ySRWR-HD1-LD1$ ySRWR-HD1-LD2$ ySRWR-HD2-LD1$ ySRWR-HD2-LD2$

0 0 0 0 0

1 873.73 1249.88 1352.91 1765.05

50 2254.84 3364.15 3641.48 4750.8

*Y ? ? ? ? SEWER ? SMALL ? WM ? MOYEN ? ? ? ? ? ? HIGH LOWDEMANDWATER ? ?

_AGE ySRWR-HD1-LD1$ ySRWR-HD1-LD2$ ySRWR-HD2-LD1$ ySRWR-HD2-LD2$

0 0 0 0 0

1 1249.88 2337.8 1765.05 2852.97

50 3664.15 6292.39 4750.8 7650.8

*Y ? ? ? ? SEWER ? MOYEN ? WM ? SMALL ? ? ? ? ? ? HIGH LOWDEMANDWATER ? ?

_AGE ySRWR-HD1-LD1$ ySRWR-HD1-LD2$ ySRWR-HD2-LD1$ ySRWR-HD2-LD2$

0 0 0 0 0

1 1352.91 1765.05 2712.81 3124.95

50 3641.48 4750.8 7301.77 8411.09

*Y ? ? ? ? SEWER ? MOYEN ? WM ? MOYEN ? ? ? ? ? ? HIGH LOWDEMANDWATER ? ?

_AGE ySRWR-HD1-LD1$ ySRWR-HD1-LD2$ ySRWR-HD2-LD1$ ySRWR-HD2-LD2$

0 0 0 0 0

1 1765.05 2852.97 3124.95 4212.87

50 4750.8 7679.03 8411.09 11339.32

*Y ? ? ? ? SEWER ? LARGE ? WM ? SMALL ? ? ? ? ? ? HIGH LOWDEMANDWATER ? ?

_AGE ySRWR-HD1-LD1$ ySRWR-HD1-LD2$ ySRWR-HD2-LD1$ ySRWR-HD2-LD2$

0 0 0 0 0

1 2712.81 3124.95 3184.83 3596.97

50 7301.77 8411.09 8572.24 9681.56

*Y ? ? ? ? SEWER ? LARGE ? WM ? MOYEN ? ? ? ? ? ? HIGH LOWDEMANDWATER ? ?

_AGE ySRWR-HD1-LD1$ ySRWR-HD1-LD2$ ySRWR-HD2-LD1$ ySRWR-HD2-LD2$

0 0 0 0 0

1 3124.95 4212.87 3596.97 4684.89

50 8411.09 11339.32 9681.56 12609.79

*Y ? ? ? ? SEWER ? SMALL ? WM ? SMALL ? ? ? ? ? ? HIGH HIGH ? ?

_AGE ySRWR-HD1-HD1$ ySRWR-HD1-HD2$ ySRWR-HD2-HD1$ ySRWR-HD2-HD2$

0 0 0 0 0

1 873.73 1249.88 1352.91 1765.05

50 2254.84 3364.15 3641.48 4750.8

*Y ? ? ? ? SEWER ? SMALL ? WM ? MOYEN ? ? ? ? ? ? HIGH HIGH ? ?

_AGE ySRWR-HD1-HD1$ ySRWR-HD1-HD2$ ySRWR-HD2-HD1$ ySRWR-HD2-HD2$

0 0 0 0 0

1 1249.88 2337.8 1765.05 2852.97

50 3664.15 6292.39 4750.8 7650.8

*Y ? ? ? ? SEWER ? MOYEN ? WM ? SMALL ? ? ? ? ? ? HIGH HIGH ? ?

_AGE ySRWR-HD1-HD1$ ySRWR-HD1-HD2$ ySRWR-HD2-HD1$ ySRWR-HD2-HD2$

0 0 0 0 0

1 1352.91 1765.05 2712.81 3124.95

50 3641.48 4750.8 7301.77 8411.09

*Y ? ? ? ? SEWER ? MOYEN ? WM ? MOYEN ? ? ? ? ? ? HIGH HIGH ? ?

_AGE ySRWR-HD1-HD1$ ySRWR-HD1-HD2$ ySRWR-HD2-HD1$ ySRWR-HD2-HD2$

0 0 0 0 0

1 1765.05 2852.97 3124.95 4212.87

50 4750.8 7679.03 8411.09 11339.32

*Y ? ? ? ? SEWER ? LARGE ? WM ? SMALL ? ? ? ? ? ? HIGH HIGH ? ?

_AGE ySRWR-HD1-HD1$ ySRWR-HD1-HD2$ ySRWR-HD2-HD1$ ySRWR-HD2-HD2$

0 0 0 0 0

1 2712.81 3124.95 3184.83 3596.97

50 7301.77 8411.09 8572.24 9681.56

*Y ? ? ? ? SEWER ? LARGE ? WM ? MOYEN ? ? ? ? ? ? HIGH HIGH ? ?

_AGE ySRWR-HD1-HD1$ ySRWR-HD1-HD2$ ySRWR-HD2-HD1$ ySRWR-HD2-HD2$

0 0 0 0 0

1 3124.95 4212.87 3596.97 4684.89

50 8411.09 11339.32 9681.56 12609.79

*Y ? ? ? ? SEWER ? ? ? WM ? ? ? ? ? ? ? ? ? ? ? ?

_AGE ySRWR-LD1-LD1! ySRWR-LD1-LD2! ySRWR-LD2-LD1! ySRWR-LD2-LD2! ySRWR-HD1-HD1! ySRWR-HD1-HD2! ySRWR-HD2-HD1! ySRWR-HD2-HD2! ySRWR-LD1-HD1! ySRWR-LD1-HD2! ySRWR-LD2-HD1! ySRWR-LD2-HD2! ySRWR-HD1-LD1! ySRWR-HD1-LD2! ySRWR-HD2-LD1! ySRWR-HD2-LD2!

0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0

1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1

50 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1

*Y ? ? ? ? SEWER ? SMALL ? WM ? SMALL ? ? ? ? ? ? ? ? ? ?

_AGE ySRWR-LD1-LD1L ySRWR-LD1-LD2L ySRWR-LD2-LD1L ySRWR-LD2-LD2L ySRWR-HD1-HD1L ySRWR-HD1-HD2L ySRWR-HD2-HD1L ySRWR-HD2-HD2L ySRWR-LD1-HD1L ySRWR-LD1-HD2L ySRWR-LD2-HD1L ySRWR-LD2-HD2L ySRWR-HD1-LD1L ySRWR-HD1-LD2L ySRWR-HD2-LD1L ySRWR-HD2-LD2L

0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0

1 2.5 3 3 3.5 2.5 3 3 3.5 3
3.5 3.5 4 3 3.5 3.5 4

50 2.5 3 3 3.5 2.5 3 3 3.5 3
3.5 3.5 4 3 3.5 3.5 4

*Y ? ? ? ? SEWER ? SMALL ? WM ? MOYEN ? ? ? ? ? ? ? ? ? ?

_AGE ySRWR-LD1-LD1L ySRWR-LD1-LD2L ySRWR-LD2-LD1L ySRWR-LD2-LD2L ySRWR-HD1-HD1L ySRWR-HD1-HD2L ySRWR-HD2-HD1L ySRWR-HD2-HD2L ySRWR-LD1-HD1L ySRWR-LD1-HD2L ySRWR-LD2-HD1L ySRWR-LD2-HD2L ySRWR-HD1-LD1L ySRWR-HD1-LD2L ySRWR-HD2-LD1L ySRWR-HD2-LD2L

0 0 0 0 0 0 0 0 0 0
0 0 0 0 0 0 0

1 3 3.5 3.5 4 3 3.5 3.5 4 3.5
4 4 4.5 3.5 4 4 4.5

50 3 3.5 3.5 4 3 3.5 3.5 4 3.5
4 4 4.5 3.5 4 4 4.5

*Y ? ? ? ? SEWER ? MOYEN ? WM ? SMALL ? ? ? ? ? ? ? ? ? ?

_AGE ySRWR-LD1-LD1L ySRWR-LD1-LD2L ySRWR-LD2-LD1L ySRWR-LD2-LD2L ySRWR-HD1-HD1L ySRWR-HD1-HD2L ySRWR-HD2-HD1L ySRWR-HD2-HD2L ySRWR-LD1-HD1L ySRWR-LD1-HD2L ySRWR-LD2-HD1L ySRWR-LD2-HD2L ySRWR-HD1-LD1L ySRWR-HD1-LD2L ySRWR-HD2-LD1L ySRWR-HD2-LD2L

0 0 0 0 0 0 0 0 0 0
0 0 0 0 0 0 0

1 3 3.5 3.5 4 3 3.5 3.5 4 3.5
4 4 4.5 3.5 4 4 4.5

50 3 3.5 3.5 4 3 3.5 3.5 4 3.5
4 4 4.5 3.5 4 4 4.5

*Y ? ? ? ? SEWER ? MOYEN ? WM ? MOYEN ? ? ? ? ? ? ? ? ? ?

_AGE ySRWR-LD1-LD1L ySRWR-LD1-LD2L ySRWR-LD2-LD1L ySRWR-LD2-LD2L ySRWR-HD1-HD1L ySRWR-HD1-HD2L ySRWR-HD2-HD1L ySRWR-HD2-HD2L ySRWR-LD1-HD1L ySRWR-LD1-HD2L ySRWR-LD2-HD1L ySRWR-LD2-HD2L ySRWR-HD1-LD1L ySRWR-HD1-LD2L ySRWR-HD2-LD1L ySRWR-HD2-LD2L

0 0 0 0 0 0 0 0 0 0
0 0 0 0 0 0 0

1 4 4.5 4.5 5 4 4.5 4.5 5 4
4.5 4.5 5 4 4.5 4.5 5

50 4 4.5 4.5 5 4 4.5 4.5 5 4
4.5 4.5 5 4 4.5 4.5 5

*Y ? ? ? ? SEWER ? LARGE ? WM ? SMALL ? ? ? ? ? ? ? ? ? ?

_AGE ySRWR-LD1-LD1L ySRWR-LD1-LD2L ySRWR-LD2-LD1L ySRWR-LD2-LD2L ySRWR-HD1-HD1L ySRWR-HD1-HD2L ySRWR-HD2-HD1L ySRWR-HD2-HD2L ySRWR-LD1-HD1L ySRWR-LD1-HD2L ySRWR-LD2-HD1L ySRWR-LD2-HD2L ySRWR-HD1-LD1L ySRWR-HD1-LD2L ySRWR-HD2-LD1L ySRWR-HD2-LD2L

0 0 0 0 0 0 0 0 0 0
0 0 0 0 0 0 0

1 4 4.5 4.5 5 4 4.5 4.5 5 4
4.5 4.5 5 4 4.5 4.5 5

50 4 4.5 4.5 5 4 4.5 4.5 5 4
4.5 4.5 5 4 4.5 4.5 5

*Y ? ? ? ? SEWER ? LARGE ? WM ? MOYEN ? ? ? ? ? ? ? ? ? ?

_AGE ySRWR-LD1-LD1L ySRWR-LD1-LD2L ySRWR-LD2-LD1L ySRWR-LD2-LD2L ySRWR-HD1-HD1L ySRWR-HD1-HD2L ySRWR-HD2-HD1L ySRWR-HD2-HD2L ySRWR-LD1-HD1L ySRWR-LD1-HD2L ySRWR-LD2-HD1L ySRWR-LD2-HD2L ySRWR-HD1-LD1L ySRWR-HD1-LD2L ySRWR-HD2-LD1L ySRWR-HD2-LD2L

0 0 0 0 0 0 0 0 0 0
0 0 0 0 0 0 0

1 4.5 5 5 5.5 4.5 5 5 5.5 5
5.5 5.5 6 5 5.5 5.5 6

50 4.5 5 5 5.5 4.5 5 5 5.5 5
5.5 5.5 6 5 5.5 5.5 6

;-- ROADS, WATER AND SEWER PIPES' INTERVENTIONS IMPACTS COST - CONDITION IMPROVEMENT - TIME - SPACE - RISK ==> Will be calculated in output per traffic distribution and reliability inverse (probability of failure)

*Y ROADS ? ? ? SEWER ? SMALL ? WM ? SMALL ? ? ? ? ? ? LOWDEMANDSEWER LOWDEMANDWATER ? ?

_AGE yRWS-LD1-LD1$ yRWS-LD1-LD2$ yRWS-LD2-LD1$ yRWS-LD2-LD2$

0 0 0 0 0

1 867.73 1279.88 1382.91 1795.05

50 2335.58 3444.9 3722.23 4750.8

*Y ROADS ? ? ? SEWER ? SMALL ? WM ? MOYEN ? ? ? ? ? ? LOWDEMANDSEWER LOWDEMANDWATER ? ?

_AGE yRWS-LD1-HD1$ yRWS-LD1-HD2$ yRWS-LD2-HD1$ yRWS-LD2-HD2$

0 0 0 0 0

1 1279.88 2367.8 1795.05 2882.97

50 3664.15 6373.13 4831.55 7650.8

*Y ROADS ? ? ? SEWER ? MOYEN ? WM ? SMALL ? ? ? ? ? ? LOWDEMANDSEWER LOWDEMANDWATER ? ?

_AGE yRWS-LD1-HD1$ yRWS-LD1-HD2$ yRWS-LD2-HD1$ yRWS-LD2-HD2$

0 0 0 0 0

1 1382.91 1795.05 2742.81 3154.95

50 3722.23 4831.55 7382.52 8491.84

*Y ROADS ? ? ? SEWER ? MOYEN ? WM ? MOYEN ? ? ? ? ? ? LOWDEMANDSEWER LOWDEMANDWATER ? ?

_AGE yRWS-LD1-HD1$ yRWS-LD1-HD2$ yRWS-LD2-HD1$ yRWS-LD2-HD2$

0 0 0 0 0

1 1795.05 2882.97 3154.95 4242.87

50 4831.55 7759.78 8491.84 11420.07

*Y ROADS ? ? ? SEWER ? LARGE ? WM ? SMALL ? ? ? ? ? ? LOWDEMANDSEWER LOWDEMANDWATER ? ?

_AGE yRWS-LD1-HD1$ yRWS-LD1-HD2$ yRWS-LD2-HD1$ yRWS-LD2-HD2$

0 0 0 0 0

1 2742.81 3154.95 3214.83 3626.97

50 7382.52 8491.84 8652.99 9762.31

*Y ROADS ? ? ? SEWER ? LARGE ? WM ? MOYEN ? ? ? ? ? ? LOWDEMANDSEWER LOWDEMANDWATER ? ?

_AGE	yRWS-LD1-HD1$	yRWS-LD1-HD2$	yRWS-LD2-HD1$	yRWS-LD2-HD2$
0	0	0	0	0
1	3154.95	4242.87	3626.97	4714.89
50	8491.84	11420.07	9762.31	12690.54

*Y ROADS ? ? ? SEWER ? SMALL ? WM ? MOYEN ? ? ? ? ? ? LOWDEMANDSEWER HIGH ? ?

_AGE	yRWS-LD1-HD1$	yRWS-LD1-HD2$	yRWS-LD2-HD1$	yRWS-LD2-HD2$
0	0	0	0	0
1	1279.88	2367.8	1795.05	2882.97
50	3664.15	6373.13	4831.55	7650.8

*Y ROADS ? ? ? SEWER ? MOYEN ? WM ? SMALL ? ? ? ? ? ? LOWDEMANDSEWER HIGH ? ?

_AGE	yRWS-LD1-HD1$	yRWS-LD1-HD2$	yRWS-LD2-HD1$	yRWS-LD2-HD2$
0	0	0	0	0
1	1382.91	1795.05	2742.81	3154.95
50	3722.23	4831.55	7382.52	8491.84

*Y ROADS ? ? ? SEWER ? MOYEN ? WM ? MOYEN ? ? ? ? ? ? LOWDEMANDSEWER HIGH ? ?

_AGE	yRWS-LD1-HD1$	yRWS-LD1-HD2$	yRWS-LD2-HD1$	yRWS-LD2-HD2$
0	0	0	0	0
1	1795.05	2882.97	3154.95	4242.87
50	4831.55	7759.78	8491.84	11420.07

*Y ROADS ? ? ? SEWER ? LARGE ? WM ? SMALL ? ? ? ? ? ? LOWDEMANDSEWER HIGH ? ?

_AGE yRWS-LD1-HD1$ yRWS-LD1-HD2$ yRWS-LD2-HD1$ yRWS-LD2-HD2$

0	0	0	0	0
1	2742.81	3154.95	3214.83	3626.97
50	7382.52	8491.84	8652.99	9762.31

*Y ROADS ? ? ? SEWER ? LARGE ? WM ? MOYEN ? ? ? ? ? ? LOWDEMANDSEWER HIGH ? ?

_AGE	yRWS-LD1-HD1$	yRWS-LD1-HD2$	yRWS-LD2-HD1$	yRWS-LD2-HD2$
0	0	0	0	0
1	3154.95	4242.87	3626.97	4714.89
50	8491.84	11420.07	9762.31	12690.54

*Y ROADS ? ? ? SEWER ? SMALL ? WM ? SMALL ? ? ? ? ? ? LOWDEMANDSEWER HIGH ? ?

_AGE	yRWS-LD1-HD1$	yRWS-LD1-HD2$	yRWS-LD2-HD1$	yRWS-LD2-HD2$
0	0	0	0	0
1	867.73	1279.88	1382.91	1795.05
50	2335.58	3444.9	3722.23	4750.8

*Y ROADS ? ? ? SEWER ? SMALL ? WM ? SMALL ? ? ? ? ? ? HIGH LOWDEMANDWATER ? ?

_AGE	yRWS-HD1-LD1$	yRWS-HD1-LD2$	yRWS-HD2-LD1$	yRWS-HD2-LD2$
0	0	0	0	0
1	867.73	1279.88	1382.91	1795.05
50	2335.58	3444.9	3722.23	4750.8

*Y ROADS ? ? ? SEWER ? SMALL ? WM ? MOYEN ? ? ? ? ? ? HIGH LOWDEMANDWATER ? ?

_AGE	yRWS-HD1-LD1$	yRWS-HD1-LD2$	yRWS-HD2-LD1$	yRWS-HD2-LD2$
0	0	0	0	0
1	1279.88	2367.8	1795.05	2882.97
50	3664.15	6373.13	4831.55	7650.8

*Y ROADS ? ? ? SEWER ? MOYEN ? WM ? SMALL ? ? ? ? ? ? HIGH LOWDEMANDWATER ? ?

_AGE yRWS-HD1-LD1$ yRWS-HD1-LD2$ yRWS-HD2-LD1$ yRWS-HD2-LD2$

0	0	0	0	0
1	1382.91	1795.05	2742.81	3154.95
50	3722.23	4831.55	7382.52	8491.84

*Y ROADS ? ? ? SEWER ? MOYEN ? WM ? MOYEN ? ? ? ? ? ? HIGH LOWDEMANDWATER ? ?

_AGE yRWS-HD1-LD1$ yRWS-HD1-LD2$ yRWS-HD2-LD1$ yRWS-HD2-LD2$

0	0	0	0	0
1	1795.05	2882.97	3154.95	4242.87
50	4831.55	7759.78	8491.84	11420.07

*Y ROADS ? ? ? SEWER ? LARGE ? WM ? SMALL ? ? ? ? ? ? HIGH LOWDEMANDWATER ? ?

_AGE yRWS-HD1-LD1$ yRWS-HD1-LD2$ yRWS-HD2-LD1$ yRWS-HD2-LD2$

0	0	0	0	0
1	2742.81	3154.95	3214.83	3626.97
50	7382.52	8491.84	8652.99	9762.31

*Y ROADS ? ? ? SEWER ? LARGE ? WM ? MOYEN ? ? ? ? ? ? HIGH LOWDEMANDWATER ? ?

_AGE yRWS-HD1-LD1$ yRWS-HD1-LD2$ yRWS-HD2-LD1$ yRWS-HD2-LD2$

0	0	0	0	0
1	3154.95	4242.87	3626.97	4714.89
50	8491.84	11420.07	9762.31	12690.54

*Y ROADS ? ? ? SEWER ? SMALL ? WM ? SMALL ? ? ? ? ? ? HIGH HIGH ? ?

_AGE yRWS-HD1-HD1$ yRWS-HD1-HD2$ yRWS-HD2-HD1$ yRWS-HD2-HD2$

0	0	0	0	0

1 867.73 1279.88 1382.91 1795.05

50 2335.58 3444.9 3722.23 4750.8

*Y ROADS ? ? ? SEWER ? SMALL ? WM ? MOYEN ? ? ? ? ? ? HIGH HIGH ? ?

_AGE yRWS-HD1-HD1$ yRWS-HD1-HD2$ yRWS-HD2-HD1$ yRWS-HD2-HD2$

0 0 0 0 0

1 1279.88 2367.8 1795.05 2882.97

50 3664.15 6373.13 4831.55 7650.8

*Y ROADS ? ? ? SEWER ? MOYEN ? WM ? SMALL ? ? ? ? ? ? HIGH HIGH ? ?

_AGE yRWS-HD1-HD1$ yRWS-HD1-HD2$ yRWS-HD2-HD1$ yRWS-HD2-HD2$

0 0 0 0 0

1 1382.91 1795.05 2742.81 3154.95

50 3722.23 4831.55 7382.52 8491.84

*Y ROADS ? ? ? SEWER ? MOYEN ? WM ? MOYEN ? ? ? ? ? ? HIGH HIGH ? ?

_AGE yRWS-HD1-HD1$ yRWS-HD1-HD2$ yRWS-HD2-HD1$ yRWS-HD2-HD2$

0 0 0 0 0

1 1795.05 2882.97 3154.95 4242.87

50 4831.55 7759.78 8491.84 11420.07

*Y ROADS ? ? ? SEWER ? LARGE ? WM ? SMALL ? ? ? ? ? ? HIGH HIGH ? ?

_AGE yRWS-HD1-HD1$ yRWS-HD1-HD2$ yRWS-HD2-HD1$ yRWS-HD2-HD2$

0 0 0 0 0

1 2742.81 3154.95 3214.83 3626.97

50 7382.52 8491.84 8652.99 9762.31

*Y ROADS ? ? ? SEWER ? LARGE ? WM ? MOYEN ? ? ? ? ? ? HIGH HIGH ? ?

_AGE yRWS-HD1-HD1$ yRWS-HD1-HD2$ yRWS-HD2-HD1$ yRWS-HD2-HD2$

0 0 0 0 0

1 3154.95 4242.87 3626.97 4714.89

50 8491.84 11420.07 9762.31 12690.54

*Y ROADS ? ? ? SEWER ? ? ? WM ? ? ? ? ? ? ? ? ? ? ? ?

_AGE yRWS-LD1-LD1! yRWS-LD1-LD2! yRWS-LD2-LD1! yRWS-LD2-LD2! yRWS-HD1-HD1! yRWS-HD1-HD2! yRWS-HD2-HD1! yRWS-HD2-HD2! yRWS-LD1-HD1! yRWS-LD1-HD2! yRWS-LD2-HD1! yRWS-LD2-HD2! yRWS-HD1-LD1! yRWS-HD1-LD2! yRWS-HD2-LD1! yRWS-HD2-LD2!

0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0

1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1

50 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1

*Y ROADS ? ? ? SEWER ? SMALL ? WM ? SMALL ? ? ? ? ? ? ? ? ? ?

_AGE yRWS-LD1-LD1L yRWS-LD1-LD2L yRWS-LD2-LD1L yRWS-LD2-LD2L yRWS-HD1-HD1L yRWS-HD1-HD2L yRWS-HD2-HD1L yRWS-HD2-HD2L yRWS-LD1-HD1L yRWS-LD1-HD2L yRWS-LD2-HD1L yRWS-LD2-HD2L yRWS-HD1-LD1L yRWS-HD1-LD2L yRWS-HD2-LD1L yRWS-HD2-LD2L

0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0

1 2.5 3 3 3.5 2.5 3 3 3.5 3 3.5 3.5 4 3 3.5 3.5 4

50 2.5 3 3 3.5 2.5 3 3 3.5 3 3.5 3.5 4 3 3.5 3.5 4

*Y ROADS ? ? ? SEWER ? SMALL ? WM ? MOYEN ? ? ? ? ? ? ? ? ? ?

_AGE yRWS-LD1-LD1L yRWS-LD1-LD2L yRWS-LD2-LD1L yRWS-LD2-LD2L yRWS-HD1-HD1L yRWS-HD1-HD2L yRWS-HD2-HD1L yRWS-HD2-HD2L yRWS-LD1-HD1L yRWS-LD1-HD2L yRWS-LD2-HD1L yRWS-LD2-HD2L yRWS-HD1-LD1L yRWS-HD1-LD2L yRWS-HD2-LD1L yRWS-HD2-LD2L

0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0

1 3 3.5 3.5 4 3 3.5 3.5 4 3.5 4 4 4.5 3.5 4 4 4.5

50 3 3.5 3.5 4 3 3.5 3.5 4 3.5
4 4 4.5 3.5 4 4 4.5

*Y ROADS ? ? ? SEWER ? MOYEN ? WM ? SMALL ? ? ? ? ? ? ? ? ? ?

_AGE yRWS-LD1-LD1L yRWS-LD1-LD2L yRWS-LD2-LD1L yRWS-LD2-LD2L yRWS-HD1-HD1L yRWS-HD1-HD2L yRWS-HD2-HD1L yRWS-HD2-HD2L yRWS-LD1-HD1L yRWS-LD1-HD2L yRWS-LD2-HD1L yRWS-LD2-HD2L yRWS-HD1-LD1L yRWS-HD1-LD2L yRWS-HD2-LD1L yRWS-HD2-LD2L

0 0 0 0 0 0 0 0 0 0 0
0 0 0 0 0 0

1 3 3.5 3.5 4 3 3.5 3.5 4 3.5
4 4 4.5 3.5 4 4 4.5

50 3 3.5 3.5 4 3 3.5 3.5 4 3.5
4 4 4.5 3.5 4 4 4.5

*Y ROADS ? ? ? SEWER ? MOYEN ? WM ? MOYEN ? ? ? ? ? ? ? ? ? ?

_AGE yRWS-LD1-LD1L yRWS-LD1-LD2L yRWS-LD2-LD1L yRWS-LD2-LD2L yRWS-HD1-HD1L yRWS-HD1-HD2L yRWS-HD2-HD1L yRWS-HD2-HD2L yRWS-LD1-HD1L yRWS-LD1-HD2L yRWS-LD2-HD1L yRWS-LD2-HD2L yRWS-HD1-LD1L yRWS-HD1-LD2L yRWS-HD2-LD1L yRWS-HD2-LD2L

0 0 0 0 0 0 0 0 0 0 0
0 0 0 0 0 0

1 4 4.5 4.5 5 4 4.5 4.5 5 4
4.5 4.5 5 4 4.5 4.5 5

50 4 4.5 4.5 5 4 4.5 4.5 5 4
4.5 4.5 5 4 4.5 4.5 5

*Y ROADS ? ? ? SEWER ? LARGE ? WM ? SMALL ? ? ? ? ? ? ? ? ? ?

_AGE yRWS-LD1-LD1L yRWS-LD1-LD2L yRWS-LD2-LD1L yRWS-LD2-LD2L yRWS-HD1-HD1L yRWS-HD1-HD2L yRWS-HD2-HD1L yRWS-HD2-HD2L yRWS-LD1-HD1L yRWS-LD1-HD2L yRWS-LD2-HD1L yRWS-LD2-HD2L yRWS-HD1-LD1L yRWS-HD1-LD2L yRWS-HD2-LD1L yRWS-HD2-LD2L

0 0 0 0 0 0 0 0 0 0 0
0 0 0 0 0 0

1 4 4.5 4.5 5 4 4.5 4.5 5 4
4.5 4.5 5 4 4.5 4.5 5

50 4 4.5 4.5 5 4 4.5 4.5 5 4
4.5 4.5 5 4 4.5 4.5 5

*Y ROADS ? ? ? SEWER ? LARGE ? WM ? MOYEN ? ? ? ? ? ? ? ? ? ?

_AGE yRWS-LD1-LD1L yRWS-LD1-LD2L yRWS-LD2-LD1L yRWS-LD2-LD2L yRWS-HD1-HD1L yRWS-HD1-HD2L yRWS-HD2-HD1L yRWS-HD2-HD2L yRWS-LD1-HD1L yRWS-LD1-HD2L yRWS-LD2-HD1L yRWS-LD2-HD2L yRWS-HD1-LD1L yRWS-HD1-LD2L yRWS-HD2-LD1L yRWS-HD2-LD2L

0 0 0 0 0 0 0 0 0 0 0
0 0 0 0 0 0

1 4.5 5 5 5.5 4.5 5 5 5.5 5
5.5 5.5 6 5 5.5 5.5 6

50 4.5 5 5 5.5 4.5 5 5 5.5 5
5.5 5.5 6 5 5.5 5.5 6

8.5.7 *Outputs*

; RELIABILITY_DEMAND/CAPATICY (RESILIENCE)_RISK

*OUTPUT ototlength
*SOURCE ? _INVENT _AREA

*OUTPUT ototalcapSR
*SOURCE ? _INVENT ycapsewer

*OUTPUT ototalcapWR
*SOURCE ? _INVENT ycapwater

*OUTPUT oRELSR
*SOURCE ? _INVENT yreliabilitySR

*OUTPUT oRELWR
*SOURCE ? _INVENT yreliabilityWR

*OUTPUT oPCIRD
*SOURCE ? _INVENT ytPCIroads

*OUTPUT oavrgRELSR
*SOURCE oRELSR / ototlength

*OUTPUT oavrgRELWR
*SOURCE oRELWR / ototlength

*OUTPUT oavrgPCIRD

```
*SOURCE oPCIRD / ototlength

*OUTPUT oavrgcapSR
*SOURCE ototalcapSR / ototlength

*OUTPUT oavrgcapWR
*SOURCE ototalcapWR / ototlength

*OUTPUT oavrgcapSRWR1
*SOURCE oavrgcapWR + oavrgcapSR

*OUTPUT oavrgcapSRWR
*SOURCE oavrgcapSRWR1 / 2

*OUTPUT oavrgRELCOR1
*SOURCE oavrgPCIRD + oavrgRELWR + oavrgRELSR

*OUTPUT oavrgRELCOR
*SOURCE oavrgRELCOR1 / 3

*OUTPUT dummy
*SOURCE ototlength / ototlength

*OUTPUT dummy2
*SOURCE dummy * 100

*OUTPUT oavrgPOFRD
*SOURCE dummy2 - oavrgPCIRD

*OUTPUT oavrgPOFSR
*SOURCE dummy2 - oavrgRELSR

*OUTPUT oavrgPOFWR
*SOURCE dummy2 - oavrgRELWR

*OUTPUT oRSKRD
*SOURCE oavrgPOFRD

*OUTPUT oRSKSR
*SOURCE oavrgPOFSR

*OUTPUT oRSKWR
*SOURCE oavrgPOFWR

*OUTPUT oRSKWRD
*SOURCE oRSKRD * 0.45
```

```
*OUTPUT oRSKWSR
*SOURCE oRSKSR * 0.25

*OUTPUT oRSKWWR
*SOURCE oRSKWR * 0.3

*OUTPUT oRSKCOR1
*SOURCE oRSKWRD + oRSKWWR + oRSKWSR

*OUTPUT oRSKCOR
*SOURCE oRSKCOR1

;__COST_TIME_SPACE ROADS SILO ACTIONS

*OUTPUT ototalCSA
*SOURCE ? ? ? ? ? ? ? ? ? ? ? ? ? ? ? ? ? ? ? ? ? ? aCS _AREA

*OUTPUT ototalCSC
*SOURCE ? ? ? ? ? ? ? ? ? ? ? ? ? ? ? ? ? ? ? ? ? ? _INVENT yCS$

*OUTPUT ototalCST
*SOURCE ? ? ? ? ? ? ? ? ? ? ? ? ? ? ? ? ? ? ? ? ? ? _INVENT yCSL

*OUTPUT ototalCSS
*SOURCE ? ? ? ? ? ? ? ? ? ? ? ? ? ? ? ? ? ? ? ? ? ? _INVENT yCS!

*OUTPUT ototalCSCT
*SOURCE ototalCSA * ototalCSC / 10000

*OUTPUT ototalCSTT
*SOURCE ototalCSA * ototalCST / 10000

*OUTPUT ototalCSST
*SOURCE ototalCSA * ototalCSS / 10000

*OUTPUT ototalMSA
*SOURCE ? ? ? ? ? ? ? ? ? ? ? ? ? ? ? ? ? ? ? ? ? ? aMS _AREA

*OUTPUT ototalMSC
*SOURCE ? ? ? ? ? ? ? ? ? ? ? ? ? ? ? ? ? ? ? ? ? ? _INVENT yMS$

*OUTPUT ototalMST
*SOURCE ? ? ? ? ? ? ? ? ? ? ? ? ? ? ? ? ? ? ? ? ? ? _INVENT yMSL

*OUTPUT ototalMSS
```

```
*SOURCE ? ? ? ? ? ? ? ? ? ? ? ? ? ? ? ? ? ? ? ? ? _INVENT yMS!

*OUTPUT ototalMSCT
*SOURCE ototalMSA * ototalMSC / 10000

*OUTPUT ototalMSTT
*SOURCE ototalMSA * ototalMST / 10000

*OUTPUT ototalMSST
*SOURCE ototalMSA * ototalMSS / 10000

*OUTPUT ototalPAA
*SOURCE ? ? ? ? ? ? ? ? ? ? ? ? ? ? ? ? ? ? ? ? ? aPA _AREA

*OUTPUT ototalPAC
*SOURCE ? ? ? ? ? ? ? ? ? ? ? ? ? ? ? ? ? ? ? ? ? _INVENT yPA$

*OUTPUT ototalPAT
*SOURCE ? ? ? ? ? ? ? ? ? ? ? ? ? ? ? ? ? ? ? ? ? _INVENT yPAL

*OUTPUT ototalPAS
*SOURCE ? ? ? ? ? ? ? ? ? ? ? ? ? ? ? ? ? ? ? ? ? _INVENT yPA!

*OUTPUT ototalPACT
*SOURCE ototalPAA * ototalPAC / 10000

*OUTPUT ototalPATT
*SOURCE ototalPAA * ototalPAT  / 10000

*OUTPUT ototalPAST
*SOURCE ototalPAA * ototalPAS / 10000

*OUTPUT ototalRSA
*SOURCE ? ? ? ? ? ? ? ? ? ? ? ? ? ? ? ? ? ? ? ? ? aRS _AREA

*OUTPUT ototalRSC
*SOURCE ? ? ? ? ? ? ? ? ? ? ? ? ? ? ? ? ? ? ? ? ? _INVENT yRS$

*OUTPUT ototalRST
*SOURCE ? ? ? ? ? ? ? ? ? ? ? ? ? ? ? ? ? ? ? ? ? _INVENT yRSL

*OUTPUT ototalRSS
*SOURCE ? ? ? ? ? ? ? ? ? ? ? ? ? ? ? ? ? ? ? ? ? _INVENT yRS!

*OUTPUT ototalRSCT
*SOURCE ototalRSA * ototalRSC / 10000
```

```
*OUTPUT ototalRSTT
*SOURCE ototalRSA * ototalRST / 10000

*OUTPUT ototalRSST
*SOURCE ototalRSA * ototalRSS / 10000

*OUTPUT ototalRCA
*SOURCE ? ? ? ? ? ? ? ? ? ? ? ? ? ? ? ? ? ? ? ? ? ? aRC _AREA

*OUTPUT ototalRCC
*SOURCE ? ? ? ? ? ? ? ? ? ? ? ? ? ? ? ? ? ? ? ? ? ? _INVENT yRC$

*OUTPUT ototalRCT
*SOURCE ? ? ? ? ? ? ? ? ? ? ? ? ? ? ? ? ? ? ? ? ? ? _INVENT yRCL

*OUTPUT ototalRCS
*SOURCE ? ? ? ? ? ? ? ? ? ? ? ? ? ? ? ? ? ? ? ? ? ? _INVENT yRC!

*OUTPUT ototalRCCT
*SOURCE ototalRCA * ototalRCC / 20000

*OUTPUT ototalRCTT
*SOURCE ototalRCA * ototalRCT / 10000

*OUTPUT ototalRCST
*SOURCE ototalRCA * ototalRCS / 10000

*OUTPUT ototalRDSCOSTSILO
*SOURCE ototalRCCT + ototalRSCT + ototalPACT + ototalMSCT + ototalCSCT

*OUTPUT ototalRDSTIMESILO
*SOURCE ototalRCTT + ototalRSTT + ototalPATT + ototalMSTT + ototalCSTT

*OUTPUT ototalRDSSPACESILO
*SOURCE ototalRCST + ototalRSST + ototalPAST + ototalMSST + ototalCSST

;__ COST_TIME_SPACE WATER

*OUTPUT ototalLWLD1A
*SOURCE ? ? ? ? ? ? ? ? ? ? ? ? ? ? ? ? ? ? ? ? ? ? alinerwater_LD1 _AREA

*OUTPUT ototalLWLD2A
*SOURCE ? ? ? ? ? ? ? ? ? ? ? ? ? ? ? ? ? ? ? ? ? ? alinerwater_LD2 _AREA

*OUTPUT ototalLWHD1A
```

*SOURCE ? alinerwater_HD1 _AREA

*OUTPUT ototalLWHD2A
*SOURCE ? alinerwater_HD2 _AREA

*OUTPUT ototalRWLD1A
*SOURCE ? areplacewater_LD1 _AREA

*OUTPUT ototalRWLD2A
*SOURCE ? areplacewater_LD2 _AREA

*OUTPUT ototalRWHD1A
*SOURCE ? areplacewater_HD1 _AREA

*OUTPUT ototalRWHD2A
*SOURCE ? areplacewater_HD2 _AREA

*OUTPUT ototallinerwater_LD1C
*SOURCE ? _INVENT ylinerwater-LD1$

*OUTPUT ototallinerwater_LD2C
*SOURCE ? _INVENT ylinerwater-LD2$

*OUTPUT ototallinerwater_HD1C
*SOURCE ? _INVENT ylinerwater-HD1$

*OUTPUT ototallinerwater_HD2C
*SOURCE ? _INVENT ylinerwater-HD2$

*OUTPUT ototalreplacewater_LD1C
*SOURCE ? _INVENT yreplacewater-LD1$

*OUTPUT ototalreplacewater_LD2C
*SOURCE ? _INVENT yreplacewater-LD2$

*OUTPUT ototalreplacewater_HD1C
*SOURCE ? _INVENT yreplacewater-HD1$

*OUTPUT ototalreplacewater_HD2C
*SOURCE ? _INVENT yreplacewater-HD2$

*OUTPUT ototallinerwater_LD1T
*SOURCE ? _INVENT ylinerwater-LD1L

*OUTPUT ototallinerwater_LD2T
*SOURCE ? _INVENT ylinerwater-LD2L

```
*OUTPUT ototallinerwater_HD1T
*SOURCE ? ? ? ? ? ? ? ? ? ? ? ? ? ? ? ? ? ? ? ? ? _INVENT ylinerwater-HD1L

*OUTPUT ototallinerwater_HD2T
*SOURCE ? ? ? ? ? ? ? ? ? ? ? ? ? ? ? ? ? ? ? ? ? _INVENT ylinerwater-HD2L

*OUTPUT ototalreplacewater_LD1T
*SOURCE ? ? ? ? ? ? ? ? ? ? ? ? ? ? ? ? ? ? ? ? ? _INVENT yreplacewater-LD1L

*OUTPUT ototalreplacewater_LD2T
*SOURCE ? ? ? ? ? ? ? ? ? ? ? ? ? ? ? ? ? ? ? ? ? _INVENT yreplacewater-LD2L

*OUTPUT ototalreplacewater_HD1T
*SOURCE ? ? ? ? ? ? ? ? ? ? ? ? ? ? ? ? ? ? ? ? ? _INVENT yreplacewater-HD1L

*OUTPUT ototalreplacewater_HD2T
*SOURCE ? ? ? ? ? ? ? ? ? ? ? ? ? ? ? ? ? ? ? ? ? _INVENT yreplacewater-HD2L

*OUTPUT ototallinerwater_LD1S
*SOURCE ? ? ? ? ? ? ? ? ? ? ? ? ? ? ? ? ? ? ? ? ? _INVENT ylinerwater-LD1!

*OUTPUT ototallinerwater_LD2S
*SOURCE ? ? ? ? ? ? ? ? ? ? ? ? ? ? ? ? ? ? ? ? ? _INVENT ylinerwater-LD2!

*OUTPUT ototallinerwater_HD1S
*SOURCE ? ? ? ? ? ? ? ? ? ? ? ? ? ? ? ? ? ? ? ? ? _INVENT ylinerwater-HD1!

*OUTPUT ototallinerwater_HD2S
*SOURCE ? ? ? ? ? ? ? ? ? ? ? ? ? ? ? ? ? ? ? ? ? _INVENT ylinerwater-HD2!

*OUTPUT ototalreplacewater_LD1S
*SOURCE ? ? ? ? ? ? ? ? ? ? ? ? ? ? ? ? ? ? ? ? ? _INVENT yreplacewater-LD1!

*OUTPUT ototalreplacewater_LD2S
*SOURCE ? ? ? ? ? ? ? ? ? ? ? ? ? ? ? ? ? ? ? ? ? _INVENT yreplacewater-LD2!

*OUTPUT ototalreplacewater_HD1S
*SOURCE ? ? ? ? ? ? ? ? ? ? ? ? ? ? ? ? ? ? ? ? ? _INVENT yreplacewater-HD1!

*OUTPUT ototalreplacewater_HD2S
*SOURCE ? ? ? ? ? ? ? ? ? ? ? ? ? ? ? ? ? ? ? ? ? _INVENT yreplacewater-HD2!

*OUTPUT ototalLWLD1CT
*SOURCE ototalLWLD1A * ototallinerwater_LD1C / 100000
```

*OUTPUT ototalLWLD2CT
*SOURCE ototalLWLD2A * ototallinerwater_LD2C / 100000

*OUTPUT ototalLWHD1CT
*SOURCE ototalLWHD1A * ototallinerwater_HD1C / 100000

*OUTPUT ototalLWHD2CT
*SOURCE ototalLWHD2A * ototallinerwater_HD2C / 100000

*OUTPUT ototalRWLD1CT
*SOURCE ototalRWLD1A * ototalreplacewater_LD1C / 100000

*OUTPUT ototalRWLD2CT
*SOURCE ototalRWLD2A * ototalreplacewater_LD2C / 100000

*OUTPUT ototalRWHD1CT
*SOURCE ototalRWHD1A * ototalreplacewater_HD1C / 100000

*OUTPUT ototalRWHD2CT
*SOURCE ototalRWHD2A * ototalreplacewater_HD2C / 100000

*OUTPUT ototalLWLD1TT
*SOURCE ototalLWLD1A * ototallinerwater_LD1T / 100000

*OUTPUT ototalLWLD2TT
*SOURCE ototalLWLD2A * ototallinerwater_LD2T / 100000

*OUTPUT ototalLWHD1TT
*SOURCE ototalLWHD1A * ototallinerwater_HD1T / 100000

*OUTPUT ototalLWHD2TT
*SOURCE ototalLWHD2A * ototallinerwater_HD2T / 100000

*OUTPUT ototalRWLD1TT
*SOURCE ototalRWLD1A * ototalreplacewater_LD1T / 100000

*OUTPUT ototalRWLD2TT
*SOURCE ototalRWLD2A * ototalreplacewater_LD2T / 100000

*OUTPUT ototalRWHD1TT
*SOURCE ototalRWHD1A * ototalreplacewater_HD1T / 100000

*OUTPUT ototalRWHD2TT
*SOURCE ototalRWHD2A * ototalreplacewater_HD2T / 100000

*OUTPUT ototalLWLD1ST

*SOURCE ototalLWLD1A * ototallinerwater_LD1S / 100000

*OUTPUT ototalLWLD2ST
*SOURCE ototalLWLD2A * ototallinerwater_LD2S / 100000

*OUTPUT ototalLWHD1ST
*SOURCE ototalLWHD1A * ototallinerwater_HD1S / 100000

*OUTPUT ototalLWHD2ST
*SOURCE ototalLWHD2A * ototallinerwater_HD2S / 100000

*OUTPUT ototalRWLD1ST
*SOURCE ototalRWLD1A * ototalreplacewater_LD1S / 100000

*OUTPUT ototalRWLD2ST
*SOURCE ototalRWLD2A * ototalreplacewater_LD2S / 100000

*OUTPUT ototalRWHD1ST
*SOURCE ototalRWHD1A * ototalreplacewater_HD1S / 100000

*OUTPUT ototalRWHD2ST
*SOURCE ototalRWHD2A * ototalreplacewater_HD2S / 100000

*OUTPUT ototalWRCOSTSILOLINER
*SOURCE ototalLWLD1CT + ototalLWLD2CT + ototalRWHD1CT + ototalRWHD2CT

*OUTPUT ototalWRTIMESILOLINER
*SOURCE ototalLWLD1TT + ototalLWLD2TT + ototalLWHD1TT + ototalLWHD2TT

*OUTPUT ototalWRSPACESILOLINER
*SOURCE ototalLWLD1ST + ototalLWLD2ST + ototalLWHD1ST + ototalLWHD2ST

*OUTPUT ototalWRCOSTSILOREPLACE
*SOURCE ototalRWLD1CT + ototalRWLD2CT + ototalRWHD1CT + ototalRWHD2CT

*OUTPUT ototalWRTIMESILOREPLACE
*SOURCE ototalRWLD1TT + ototalRWLD2TT + ototalRWHD1TT + ototalRWHD2TT

*OUTPUT ototalWRSPACESILOREPLACE
*SOURCE ototalRWLD1ST + ototalRWLD2ST + ototalRWHD1ST + ototalRWHD2ST

*OUTPUT ototalWRCOSTSILO
*SOURCE ototalWRCOSTSILOLINER + ototalWRCOSTSILOREPLACE

*OUTPUT ototalWRTIMESILO
*SOURCE ototalWRTIMESILOLINER + ototalWRTIMESILOREPLACE

*OUTPUT ototalWRSPACESILO
*SOURCE ototalWRSPACESILOLINER + ototalWRSPACESILOREPLACE

;____ SEWER COST_TIME_SPACE SILO

*OUTPUT ototalLSLD1A
*SOURCE ? alinersewer_LD1 _AREA

*OUTPUT ototalLSLD2A
*SOURCE ? alinersewer_LD2 _AREA

*OUTPUT ototalLSHD1A
*SOURCE ? alinersewer_HD1 _AREA

*OUTPUT ototalLSHD2A
*SOURCE ? alinersewer_HD2 _AREA

*OUTPUT ototalRSLD1A
*SOURCE ? areplacesewer_LD1 _AREA

*OUTPUT ototalRSLD2A
*SOURCE ? areplacesewer_LD2 _AREA

*OUTPUT ototalRSHD1A
*SOURCE ? areplacesewer_HD1 _AREA

*OUTPUT ototalRSHD2A
*SOURCE ? areplacesewer_HD2 _AREA

*OUTPUT ototallinersewer_LD1C
*SOURCE ? _INVENT ylinersewer-LD1$

*OUTPUT ototallinersewer_LD2C
*SOURCE ? _INVENT ylinersewer-LD2$

*OUTPUT ototallinersewer_HD1C
*SOURCE ? _INVENT ylinersewer-HD1$

*OUTPUT ototallinersewer_HD2C
*SOURCE ? _INVENT ylinersewer-HD2$

*OUTPUT ototalreplacesewer_LD1C
*SOURCE ? _INVENT yreplacesewer-LD1$

*OUTPUT ototalreplacesewer_LD2C

```
*SOURCE ? ? ? ? ? ? ? ? ? ? ? ? ? ? ? ? ? ? ? ? ? _INVENT yreplacesewer-LD2$

*OUTPUT ototalreplacesewer_HD1C
*SOURCE ? ? ? ? ? ? ? ? ? ? ? ? ? ? ? ? ? ? ? ? ? _INVENT yreplacesewer-HD1$

*OUTPUT ototalreplacesewer_HD2C
*SOURCE ? ? ? ? ? ? ? ? ? ? ? ? ? ? ? ? ? ? ? ? ? _INVENT yreplacesewer-HD2$

*OUTPUT ototallinersewer_LD1T
*SOURCE ? ? ? ? ? ? ? ? ? ? ? ? ? ? ? ? ? ? ? ? ? _INVENT ylinersewer-LD1L

*OUTPUT ototallinersewer_LD2T
*SOURCE ? ? ? ? ? ? ? ? ? ? ? ? ? ? ? ? ? ? ? ? ? _INVENT ylinersewer-LD2L

*OUTPUT ototallinersewer_HD1T
*SOURCE ? ? ? ? ? ? ? ? ? ? ? ? ? ? ? ? ? ? ? ? ? _INVENT ylinersewer-HD1L

*OUTPUT ototallinersewer_HD2T
*SOURCE ? ? ? ? ? ? ? ? ? ? ? ? ? ? ? ? ? ? ? ? ? _INVENT ylinersewer-HD2L

*OUTPUT ototalreplacesewer_LD1T
*SOURCE ? ? ? ? ? ? ? ? ? ? ? ? ? ? ? ? ? ? ? ? ? _INVENT yreplacesewer-LD1L

*OUTPUT ototalreplacesewer_LD2T
*SOURCE ? ? ? ? ? ? ? ? ? ? ? ? ? ? ? ? ? ? ? ? ? _INVENT yreplacesewer-LD2L

*OUTPUT ototalreplacesewer_HD1T
*SOURCE ? ? ? ? ? ? ? ? ? ? ? ? ? ? ? ? ? ? ? ? ? _INVENT yreplacesewer-HD1L

*OUTPUT ototalreplacesewer_HD2T
*SOURCE ? ? ? ? ? ? ? ? ? ? ? ? ? ? ? ? ? ? ? ? ? _INVENT yreplacesewer-HD2L

*OUTPUT ototallinersewer_LD1S
*SOURCE ? ? ? ? ? ? ? ? ? ? ? ? ? ? ? ? ? ? ? ? ? _INVENT ylinersewer-LD1!

*OUTPUT ototallinersewer_LD2S
*SOURCE ? ? ? ? ? ? ? ? ? ? ? ? ? ? ? ? ? ? ? ? ? _INVENT ylinersewer-LD2!

*OUTPUT ototallinersewer_HD1S
*SOURCE ? ? ? ? ? ? ? ? ? ? ? ? ? ? ? ? ? ? ? ? ? _INVENT ylinersewer-HD1!

*OUTPUT ototallinersewer_HD2S
*SOURCE ? ? ? ? ? ? ? ? ? ? ? ? ? ? ? ? ? ? ? ? ? _INVENT ylinersewer-HD2!

*OUTPUT ototalreplacesewer_LD1S
*SOURCE ? ? ? ? ? ? ? ? ? ? ? ? ? ? ? ? ? ? ? ? ? _INVENT yreplacesewer-LD1!
```

*OUTPUT ototalreplacesewer_LD2S
*SOURCE ? _INVENT yreplacesewer-LD2!

*OUTPUT ototalreplacesewer_HD1S
*SOURCE ? _INVENT yreplacesewer-HD1!

*OUTPUT ototalreplacesewer_HD2S
*SOURCE ? _INVENT yreplacesewer-HD2!

*OUTPUT ototalLSLD1CT
*SOURCE ototalLSLD1A * ototallinersewer_LD1C / 100000

*OUTPUT ototalLSLD2CT
*SOURCE ototalLSLD2A * ototallinersewer_LD2C / 100000

*OUTPUT ototalLSHD1CT
*SOURCE ototalLSHD1A * ototallinersewer_HD1C / 100000

*OUTPUT ototalLSHD2CT
*SOURCE ototalLSHD2A * ototallinersewer_HD2C / 100000

*OUTPUT ototalRSLD1CT
*SOURCE ototalRSLD1A * ototalreplacesewer_LD1C / 100000

*OUTPUT ototalRSLD2CT
*SOURCE ototalRSLD2A * ototalreplacesewer_LD2C / 100000

*OUTPUT ototalRSHD1CT
*SOURCE ototalRSHD1A * ototalreplacesewer_HD1C / 100000

*OUTPUT ototalRSHD2CT
*SOURCE ototalRSHD2A * ototalreplacesewer_HD2C / 100000

*OUTPUT ototalLSLD1TT
*SOURCE ototalLSLD1A * ototallinersewer_LD1T / 100000

*OUTPUT ototalLSLD2TT
*SOURCE ototalLSLD2A * ototallinersewer_LD2T / 100000

*OUTPUT ototalLSHD1TT
*SOURCE ototalLSHD1A * ototallinersewer_HD1T / 100000

*OUTPUT ototalLSHD2TT
*SOURCE ototalLSHD2A * ototallinersewer_HD2T / 100000

```
*OUTPUT ototalRSLD1TT
*SOURCE ototalRSLD1A * ototalreplacesewer_LD1T / 100000

*OUTPUT ototalRSLD2TT
*SOURCE ototalRSLD2A * ototalreplacesewer_LD2T / 100000

*OUTPUT ototalRSHD1TT
*SOURCE ototalRSHD1A * ototalreplacesewer_HD1T / 100000

*OUTPUT ototalRSHD2TT
*SOURCE ototalRSHD2A * ototalreplacesewer_HD2T / 100000

*OUTPUT ototalLSLD1ST
*SOURCE ototalLSLD1A * ototallinersewer_LD1S / 100000

*OUTPUT ototalLSLD2ST
*SOURCE ototalLSLD2A * ototallinersewer_LD2S / 100000

*OUTPUT ototalLSHD1ST
*SOURCE ototalLSHD1A * ototallinersewer_HD1S / 100000

*OUTPUT ototalLSHD2ST
*SOURCE ototalLSHD2A * ototallinersewer_HD2S / 100000

*OUTPUT ototalRSLD1ST
*SOURCE ototalRSLD1A * ototalreplacesewer_LD1S / 100000

*OUTPUT ototalRSLD2ST
*SOURCE ototalRSLD2A * ototalreplacesewer_LD2S / 100000

*OUTPUT ototalRSHD1ST
*SOURCE ototalRSHD1A * ototalreplacesewer_HD1S / 100000

*OUTPUT ototalRSHD2ST
*SOURCE ototalRSHD2A * ototalreplacesewer_HD2S / 100000

*OUTPUT ototalSRCOSTSILOLINER
*SOURCE ototalLSLD1CT + ototalLSLD2CT + ototalLSHD1CT + ototalLSHD2CT

*OUTPUT ototalSRTIMESILOLINER
*SOURCE ototalLSLD1TT + ototalLSLD2TT + ototalLSHD1TT + ototalLSHD2TT

*OUTPUT ototalSRSPACESILOLINER
*SOURCE ototalLSLD1ST + ototalLSLD2ST + ototalLSHD1ST + ototalLSHD2ST

*OUTPUT ototalSRCOSTSILOREPLACE
```

*SOURCE ototalRSLD1CT + ototalRSLD2CT + ototalRSHD1CT + ototalRSHD2CT

*OUTPUT ototalSRTIMESILOREPLACE
*SOURCE ototalRSLD1TT + ototalRSLD2TT + ototalRSHD1TT + ototalRSHD2TT

*OUTPUT ototalSRSPACESILOREPLACE
*SOURCE ototalRSLD1ST + ototalRSLD2ST + ototalRSHD1ST + ototalRSHD2ST

*OUTPUT ototalSRCOSTSILO
*SOURCE ototalSRCOSTSILOLINER + ototalSRCOSTSILOREPLACE

*OUTPUT ototalSRTIMESILO
*SOURCE ototalSRTIMESILOLINER + ototalSRTIMESILOREPLACE

*OUTPUT ototalSRSPACESILO
*SOURCE ototalSRSPACESILOLINER + ototalSRSPACESILOREPLACE

;__COST_TIME_SPACE for Partially combined Road and Water

*OUTPUT ototalRDWRLD1A
*SOURCE ? aRDWR_LD1 _AREA

*OUTPUT ototalRDWRLD2A
*SOURCE ? aRDWR_LD2 _AREA

*OUTPUT ototalRDWRHD1A
*SOURCE ? aRDWR_HD1 _AREA

*OUTPUT ototalRDWRHD2A
*SOURCE ? aRDWR_HD2 _AREA

*OUTPUT ototalRDWR_LD1C
*SOURCE ? _INVENT yRDWR-LD1$

*OUTPUT ototalRDWR_LD2C
*SOURCE ? _INVENT yRDWR-LD2$

*OUTPUT ototalRDWR_HD1C
*SOURCE ? _INVENT yRDWR-HD1$

*OUTPUT ototalRDWR_HD2C
*SOURCE ? _INVENT yRDWR-HD2$

*OUTPUT ototalRDWR_LD1T
*SOURCE ? _INVENT yRDWR-LD1L

*OUTPUT ototalRDWR_LD2T
*SOURCE ? _INVENT yRDWR-LD2L

*OUTPUT ototalRDWR_HD1T
*SOURCE ? _INVENT yRDWR-HD1L

*OUTPUT ototalRDWR_HD2T
*SOURCE ? _INVENT yRDWR-HD2L

*OUTPUT ototalRDWR_LD1S
*SOURCE ? _INVENT yRDWR-LD1!

*OUTPUT ototalRDWR_LD2S
*SOURCE ? _INVENT yRDWR-LD2!

*OUTPUT ototalRDWR_HD1S
*SOURCE ? _INVENT yRDWR-HD1!

*OUTPUT ototalRDWR_HD2S
*SOURCE ? _INVENT yRDWR-HD2!

*OUTPUT ototalRDWRLD1CT
*SOURCE ototalRDWRLD1A * ototalRDWR_LD1C / 10000

*OUTPUT ototalRDWRLD2CT
*SOURCE ototalRDWRLD2A * ototalRDWR_LD2C / 10000

*OUTPUT ototalRDWRHD1CT
*SOURCE ototalRDWRHD1A * ototalRDWR_HD1C / 10000

*OUTPUT ototalRDWRHD2CT
*SOURCE ototalRDWRHD2A * ototalRDWR_HD2C / 10000

*OUTPUT ototalRDWRLD1TT
*SOURCE ototalRDWRLD1A * ototalRDWR_LD1T / 10000

*OUTPUT ototalRDWRLD2TT
*SOURCE ototalRDWRLD2A * ototalRDWR_LD2T / 10000

*OUTPUT ototalRDWRHD1TT
*SOURCE ototalRDWRHD1A * ototalRDWR_HD1T / 10000

*OUTPUT ototalRDWRHD2TT
*SOURCE ototalRDWRHD2A * ototalRDWR_HD2T / 10000

*OUTPUT ototalRDWRLD1ST

*SOURCE ototalRDWRLD1A * ototalRDWR_LD1S / 10000

*OUTPUT ototalRDWRLD2ST
*SOURCE ototalRDWRLD2A * ototalRDWR_LD2S / 10000

*OUTPUT ototalRDWRHD1ST
*SOURCE ototalRDWRHD1A * ototalRDWR_HD1S / 10000

*OUTPUT ototalRDWRHD2ST
*SOURCE ototalRDWRHD2A * ototalRDWR_HD2S / 10000

*OUTPUT ototalRDWRCOSTPARTIAL
*SOURCE ototalRDWRLD1CT + ototalRDWRLD2CT + ototalRDWRHD1CT + ototalRDWRHD2CT

*OUTPUT ototalRDWRTIMEPARTIAL
*SOURCE ototalRDWRLD1TT + ototalRDWRLD2TT + ototalRDWRHD1TT + ototalRDWRHD2TT

*OUTPUT ototalRDWRSPACEPARTIAL
*SOURCE ototalRDWRLD1ST + ototalRDWRLD2ST + ototalRDWRHD1ST + ototalRDWRHD2ST

;__COST_TIME_SPACE for Partially Road and Sewer

*OUTPUT ototalRDSRLD1A
*SOURCE ? aRDSR_LD1 _AREA

*OUTPUT ototalRDSRLD2A
*SOURCE ? aRDSR_LD2 _AREA

*OUTPUT ototalRDSRHD1A
*SOURCE ? aRDSR_HD1 _AREA

*OUTPUT ototalRDSRHD2A
*SOURCE ? aRDSR_HD2 _AREA

*OUTPUT ototalRDSR_LD1C
*SOURCE ? _INVENT yRDSR-LD1$

*OUTPUT ototalRDSR_LD2C
*SOURCE ? _INVENT yRDSR-LD2$

*OUTPUT ototalRDSR_HD1C
*SOURCE ? _INVENT yRDSR-HD1$

*OUTPUT ototalRDSR_HD2C
*SOURCE ? _INVENT yRDSR-HD2$

*OUTPUT ototalRDSR_LD1T
*SOURCE ? _INVENT yRDSR-LD1L

*OUTPUT ototalRDSR_LD2T
*SOURCE ? _INVENT yRDSR-LD2L

*OUTPUT ototalRDSR_HD1T
*SOURCE ? _INVENT yRDSR-HD1L

*OUTPUT ototalRDSR_HD2T
*SOURCE ? _INVENT yRDSR-HD2L

*OUTPUT ototalRDSR_LD1S
*SOURCE ? _INVENT yRDSR-LD1!

*OUTPUT ototalRDSR_LD2S
*SOURCE ? _INVENT yRDSR-LD2!

*OUTPUT ototalRDSR_HD1S
*SOURCE ? _INVENT yRDSR-HD1!

*OUTPUT ototalRDSR_HD2S
*SOURCE ? _INVENT yRDSR-HD2!

*OUTPUT ototalRDSRLD1CT
*SOURCE ototalRDSRLD1A * ototalRDSR_LD1C / 100000

*OUTPUT ototalRDSRLD2CT
*SOURCE ototalRDSRLD2A * ototalRDSR_LD2C / 100000

*OUTPUT ototalRDSRHD1CT
*SOURCE ototalRDSRHD1A * ototalRDSR_HD1C / 100000

*OUTPUT ototalRDSRHD2CT
*SOURCE ototalRDSRHD2A * ototalRDSR_HD2C / 100000

*OUTPUT ototalRDSRLD1TT
*SOURCE ototalRDSRLD1A * ototalRDSR_LD1T / 100000

*OUTPUT ototalRDSRLD2TT
*SOURCE ototalRDSRLD2A * ototalRDSR_LD2T / 100000

*OUTPUT ototalRDSRHD1TT

*SOURCE ototalRDSRHD1A * ototalRDSR_HD1T / 100000

*OUTPUT ototalRDSRHD2TT
*SOURCE ototalRDSRHD2A * ototalRDSR_HD2T / 100000

*OUTPUT ototalRDSRLD1ST
*SOURCE ototalRDSRLD1A * ototalRDSR_LD1S / 100000

*OUTPUT ototalRDSRLD2ST
*SOURCE ototalRDSRLD2A * ototalRDSR_LD2S / 100000

*OUTPUT ototalRDSRHD1ST
*SOURCE ototalRDSRHD1A * ototalRDSR_HD1S / 100000

*OUTPUT ototalRDSRHD2ST
*SOURCE ototalRDSRHD2A * ototalRDSR_HD2S / 100000

*OUTPUT ototalRDSRCOSTPARTIAL
*SOURCE ototalRDSRLD1CT + ototalRDSRLD2CT + ototalRDSRHD1CT + ototalRDSRHD2CT

*OUTPUT ototalRDSRTIMEPARTIAL
*SOURCE ototalRDSRLD1TT + ototalRDSRLD2TT + ototalRDSRHD1TT + ototalRDSRHD2TT

*OUTPUT ototalRDSRSPACEPARTIAL
*SOURCE ototalRDSRLD1ST + ototalRDSRLD2ST + ototalRDSRHD1ST + ototalRDSRHD2ST

;__COST_TIME_SPACE for Partially combined Water and Sewer

*OUTPUT ototalSRWRLD1_LD1A
*SOURCE ? aSRWR_LD1_LD1 _AREA

*OUTPUT ototalSRWRLD1_LD2A
*SOURCE ? aSRWR_LD1_LD2 _AREA

*OUTPUT ototalSRWRLD2_LD1A
*SOURCE ? aSRWR_LD2_LD1 _AREA

*OUTPUT ototalSRWRLD2_LD2A
*SOURCE ? aSRWR_LD2_LD2 _AREA

*OUTPUT ototalSRWRHD1_HD1A
*SOURCE ? aSRWR_HD1_HD1 _AREA

*OUTPUT ototalSRWRHD1_HD2A
*SOURCE ? aSRWR_HD1_HD2 _AREA

*OUTPUT ototalSRWRHD2_HD1A
*SOURCE ? aSRWR_HD2_HD1 _AREA

*OUTPUT ototalSRWRHD2_HD2A
*SOURCE ? aSRWR_HD2_HD2 _AREA

*OUTPUT ototalSRWRLD1_HD1A
*SOURCE ? aSRWR_LD1_HD1 _AREA

*OUTPUT ototalSRWRLD1_HD2A
*SOURCE ? aSRWR_LD1_HD2 _AREA

*OUTPUT ototalSRWRLD2_HD1A
*SOURCE ? aSRWR_LD2_HD1 _AREA

*OUTPUT ototalSRWRLD2_HD2A
*SOURCE ? aSRWR_LD2_HD2 _AREA

*OUTPUT ototalSRWRHD1_LD1A
*SOURCE ? aSRWR_HD1_LD1 _AREA

*OUTPUT ototalSRWRHD1_LD2A
*SOURCE ? aSRWR_HD1_LD2 _AREA

*OUTPUT ototalSRWRHD2_LD1A
*SOURCE ? aSRWR_HD2_LD1 _AREA

*OUTPUT ototalSRWRHD2_LD2A
*SOURCE ? aSRWR_HD2_LD2 _AREA

*OUTPUT ototalSRWR_LD1_LD1C
*SOURCE ? _INVENT ySRWR-LD1-LD1$

*OUTPUT ototalSRWR_LD1_LD2C
*SOURCE ? _INVENT ySRWR-LD1-LD2$

*OUTPUT ototalSRWR_LD1_HD1C
*SOURCE ? _INVENT ySRWR-LD1-HD1$

*OUTPUT ototalSRWR_LD1_HD2C
*SOURCE ? _INVENT ySRWR-LD1-HD2$

*OUTPUT ototalSRWR_LD2_LD1C

*SOURCE ? _INVENT ySRWR-LD2-LD1$

*OUTPUT ototalSRWR_LD2_LD2C
*SOURCE ? _INVENT ySRWR-LD2-LD2$

*OUTPUT ototalSRWR_LD2_HD1C
*SOURCE ? _INVENT ySRWR-LD2-HD1$

*OUTPUT ototalSRWR_LD2_HD2C
*SOURCE ? _INVENT ySRWR-LD2-HD2$

*OUTPUT ototalSRWR_HD1_LD1C
*SOURCE ? _INVENT ySRWR-HD1-LD1$

*OUTPUT ototalSRWR_HD1_LD2C
*SOURCE ? _INVENT ySRWR-HD1-LD2$

*OUTPUT ototalSRWR_HD1_HD1C
*SOURCE ? _INVENT ySRWR-HD1-HD1$

*OUTPUT ototalSRWR_HD1_HD2C
*SOURCE ? _INVENT ySRWR-HD1-HD2$

*OUTPUT ototalSRWR_HD2_LD1C
*SOURCE ? _INVENT ySRWR-HD2-LD1$

*OUTPUT ototalSRWR_HD2_LD2C
*SOURCE ? _INVENT ySRWR-HD2-LD2$

*OUTPUT ototalSRWR_HD2_HD1C
*SOURCE ? _INVENT ySRWR-HD2-HD1$

*OUTPUT ototalSRWR_HD2_HD2C
*SOURCE ? _INVENT ySRWR-HD2-HD2$

*OUTPUT ototalSRWR_LD1_LD1T
*SOURCE ? _INVENT ySRWR-LD1-LD1L

*OUTPUT ototalSRWR_LD1_LD2T
*SOURCE ? _INVENT ySRWR-LD1-LD2L

*OUTPUT ototalSRWR_LD1_HD1T
*SOURCE ? _INVENT ySRWR-LD1-HD1L

*OUTPUT ototalSRWR_LD1_HD2T
*SOURCE ? _INVENT ySRWR-LD1-HD2L

*OUTPUT ototalSRWR_LD2_LD1T
*SOURCE ? _INVENT ySRWR-LD2-LD1L

*OUTPUT ototalSRWR_LD2_LD2T
*SOURCE ? _INVENT ySRWR-LD2-LD2L

*OUTPUT ototalSRWR_LD2_HD1T
*SOURCE ? _INVENT ySRWR-LD2-HD1L

*OUTPUT ototalSRWR_LD2_HD2T
*SOURCE ? _INVENT ySRWR-LD2-HD2L

*OUTPUT ototalSRWR_HD1_LD1T
*SOURCE ? _INVENT ySRWR-HD1-LD1L

*OUTPUT ototalSRWR_HD1_LD2T
*SOURCE ? _INVENT ySRWR-HD1-LD2L

*OUTPUT ototalSRWR_HD1_HD1T
*SOURCE ? _INVENT ySRWR-HD1-HD1L

*OUTPUT ototalSRWR_HD1_HD2T
*SOURCE ? _INVENT ySRWR-HD1-HD2L

*OUTPUT ototalSRWR_HD2_LD1T
*SOURCE ? _INVENT ySRWR-HD2-LD1L

*OUTPUT ototalSRWR_HD2_LD2T
*SOURCE ? _INVENT ySRWR-HD2-LD2L

*OUTPUT ototalSRWR_HD2_HD1T
*SOURCE ? _INVENT ySRWR-HD2-HD1L

*OUTPUT ototalSRWR_HD2_HD2T
*SOURCE ? _INVENT ySRWR-HD2-HD2L

*OUTPUT ototalSRWR_LD1_LD1S
*SOURCE ? _INVENT ySRWR-LD1-LD1!

*OUTPUT ototalSRWR_LD1_LD2S
*SOURCE ? _INVENT ySRWR-LD1-LD2!

*OUTPUT ototalSRWR_LD1_HD1S
*SOURCE ? _INVENT ySRWR-LD1-HD1!

*OUTPUT ototalSRWR_LD1_HD2S
*SOURCE ? _INVENT ySRWR-LD1-HD2!

*OUTPUT ototalSRWR_LD2_LD1S
*SOURCE ? _INVENT ySRWR-LD2-LD1!

*OUTPUT ototalSRWR_LD2_LD2S
*SOURCE ? _INVENT ySRWR-LD2-LD2!

*OUTPUT ototalSRWR_LD2_HD1S
*SOURCE ? _INVENT ySRWR-LD2-HD1!

*OUTPUT ototalSRWR_LD2_HD2S
*SOURCE ? _INVENT ySRWR-LD2-HD2!

*OUTPUT ototalSRWR_HD1_LD1S
*SOURCE ? _INVENT ySRWR-HD1-LD1!

*OUTPUT ototalSRWR_HD1_LD2S
*SOURCE ? _INVENT ySRWR-HD1-LD2!

*OUTPUT ototalSRWR_HD1_HD1S
*SOURCE ? _INVENT ySRWR-HD1-HD1!

*OUTPUT ototalSRWR_HD1_HD2S
*SOURCE ? _INVENT ySRWR-HD1-HD2!

*OUTPUT ototalSRWR_HD2_LD1S
*SOURCE ? _INVENT ySRWR-HD2-LD1!

*OUTPUT ototalSRWR_HD2_LD2S
*SOURCE ? _INVENT ySRWR-HD2-LD2!

*OUTPUT ototalSRWR_HD2_HD1S
*SOURCE ? _INVENT ySRWR-HD2-HD1!

*OUTPUT ototalSRWR_HD2_HD2S
*SOURCE ? _INVENT ySRWR-HD2-HD2!

*OUTPUT ototalSRWRLD1_LD1CT
*SOURCE ototalSRWRLD1_LD1A * ototalSRWR_LD1_LD1C / 100000

*OUTPUT ototalSRWRLD1_LD2CT
*SOURCE ototalSRWRLD1_LD2A * ototalSRWR_LD1_LD2C / 100000

*OUTPUT ototalSRWRLD1_HD1CT

*SOURCE ototalSRWRLD1_HD1A * ototalSRWR_LD1_HD1C / 100000

*OUTPUT ototalSRWRLD1_HD2CT
*SOURCE ototalSRWRLD1_HD2A * ototalSRWR_LD1_HD2C / 100000

*OUTPUT ototalSRWRLD2_LD1CT
*SOURCE ototalSRWRLD2_LD1A * ototalSRWR_LD2_LD1C / 100000

*OUTPUT ototalSRWRLD2_LD2CT
*SOURCE ototalSRWRLD2_LD2A * ototalSRWR_LD2_LD2C / 100000

*OUTPUT ototalSRWRLD2_HD1CT
*SOURCE ototalSRWRLD2_HD1A * ototalSRWR_LD2_HD1C / 100000

*OUTPUT ototalSRWRLD2_HD2CT
*SOURCE ototalSRWRLD2_HD2A * ototalSRWR_LD2_HD2C / 100000

*OUTPUT ototalSRWRHD1_LD1CT
*SOURCE ototalSRWRHD1_LD1A * ototalSRWR_HD1_LD1C / 100000

*OUTPUT ototalSRWRHD1_LD2CT
*SOURCE ototalSRWRHD1_LD2A * ototalSRWR_HD1_LD2C / 100000

*OUTPUT ototalSRWRHD1_HD1CT
*SOURCE ototalSRWRHD1_HD1A * ototalSRWR_HD1_HD1C / 100000

*OUTPUT ototalSRWRHD1_HD2CT
*SOURCE ototalSRWRHD1_HD2A * ototalSRWR_HD1_HD2C / 100000

*OUTPUT ototalSRWRHD2_LD1CT
*SOURCE ototalSRWRHD2_LD1A * ototalSRWR_HD2_LD1C / 100000

*OUTPUT ototalSRWRHD2_LD2CT
*SOURCE ototalSRWRHD2_LD2A * ototalSRWR_HD2_LD2C / 100000

*OUTPUT ototalSRWRHD2_HD1CT
*SOURCE ototalSRWRHD2_HD1A * ototalSRWR_HD2_HD1C / 100000

*OUTPUT ototalSRWRHD2_HD2CT
*SOURCE ototalSRWRHD2_HD2A * ototalSRWR_HD2_HD2C / 100000

*OUTPUT ototalSRWRLD1_LD1TT
*SOURCE ototalSRWRLD1_LD1A * ototalSRWR_LD1_LD1T / 100000

*OUTPUT ototalSRWRLD1_LD2TT
*SOURCE ototalSRWRLD1_LD2A * ototalSRWR_LD1_LD2T / 100000

*OUTPUT ototalSRWRLD1_HD1TT
*SOURCE ototalSRWRLD1_HD1A * ototalSRWR_LD1_HD1T / 100000

*OUTPUT ototalSRWRLD1_HD2TT
*SOURCE ototalSRWRLD1_HD2A * ototalSRWR_LD1_HD2T / 100000

*OUTPUT ototalSRWRLD2_LD1TT
*SOURCE ototalSRWRLD2_LD1A * ototalSRWR_LD2_LD1T / 100000

*OUTPUT ototalSRWRLD2_LD2TT
*SOURCE ototalSRWRLD2_LD2A * ototalSRWR_LD2_LD2T / 100000

*OUTPUT ototalSRWRLD2_HD1TT
*SOURCE ototalSRWRLD2_HD1A * ototalSRWR_LD2_HD1T / 100000

*OUTPUT ototalSRWRLD2_HD2TT
*SOURCE ototalSRWRLD2_HD2A * ototalSRWR_LD2_HD2T / 100000

*OUTPUT ototalSRWRHD1_LD1TT
*SOURCE ototalSRWRHD1_LD1A * ototalSRWR_HD1_LD1T / 100000

*OUTPUT ototalSRWRHD1_LD2TT
*SOURCE ototalSRWRHD1_LD2A * ototalSRWR_HD1_LD2T / 100000

*OUTPUT ototalSRWRHD1_HD1TT
*SOURCE ototalSRWRHD1_HD1A * ototalSRWR_HD1_HD1T / 100000

*OUTPUT ototalSRWRHD1_HD2TT
*SOURCE ototalSRWRHD1_HD2A * ototalSRWR_HD1_HD2T / 100000

*OUTPUT ototalSRWRHD2_LD1TT
*SOURCE ototalSRWRHD2_LD1A * ototalSRWR_HD2_LD1T / 100000

*OUTPUT ototalSRWRHD2_LD2TT
*SOURCE ototalSRWRHD2_LD2A * ototalSRWR_HD2_LD2T / 100000

*OUTPUT ototalSRWRHD2_HD1TT
*SOURCE ototalSRWRHD2_HD1A * ototalSRWR_HD2_HD1T / 100000

*OUTPUT ototalSRWRHD2_HD2TT
*SOURCE ototalSRWRHD2_HD2A * ototalSRWR_HD2_HD2T / 100000

*OUTPUT ototalSRWRLD1_LD1ST
*SOURCE ototalSRWRLD1_LD1A * ototalSRWR_LD1_LD1S / 100000

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*OUTPUT ototalSRWRLD1_LD2ST
*SOURCE ototalSRWRLD1_LD2A * ototalSRWR_LD1_LD2S / 100000

*OUTPUT ototalSRWRHD2_HD1ST
*SOURCE ototalSRWRHD2_HD1A * ototalSRWR_HD2_HD1S / 100000

*OUTPUT ototalSRWRHD2_HD2ST
*SOURCE ototalSRWRHD2_HD2A * ototalSRWR_HD2_HD2S / 100000

*OUTPUT ototalSRWRCOSTPARTIAL1
*SOURCE ototalSRWRLD1_LD1CT + ototalSRWRLD1_LD2CT + ototalSRWRLD1_HD1CT
+ ototalSRWRLD1_HD2CT + ototalSRWRLD2_LD1CT + ototalSRWRLD2_LD2CT +
ototalSRWRLD2_HD1CT + ototalSRWRLD2_HD2CT + ototalSRWRHD1_LD1CT +
ototalSRWRHD1_LD2CT + ototalSRWRHD1_HD1CT

*OUTPUT ototalSRWRTIMEPARTIAL1
*SOURCE ototalSRWRLD1_LD1TT + ototalSRWRLD1_LD2TT + ototalSRWRLD1_HD1TT
+ ototalSRWRLD1_HD2TT + ototalSRWRLD2_LD1TT + ototalSRWRLD2_LD2TT +
ototalSRWRLD2_HD1TT + ototalSRWRLD2_HD2TT + ototalSRWRHD1_LD1TT +
ototalSRWRHD1_LD2TT + ototalSRWRHD1_HD1TT

*OUTPUT ototalSRWRSPACEPARTIAL1
*SOURCE ototalSRWRLD1_LD1ST + ototalSRWRLD1_LD2ST + ototalSRWRLD1_HD1ST
+ ototalSRWRLD1_HD2ST + ototalSRWRLD2_LD1ST + ototalSRWRLD2_LD2ST +
ototalSRWRLD2_HD1ST + ototalSRWRLD2_HD2ST + ototalSRWRHD1_LD1ST +
ototalSRWRHD1_LD2ST + ototalSRWRHD1_HD1ST

*OUTPUT ototalSRWRCOSTPARTIAL
*SOURCE ototalSRWRCOSTPARTIAL1 + ototalSRWRHD1_HD2CT

*OUTPUT ototalSRWRTIMEPARTIAL
*SOURCE ototalSRWRTIMEPARTIAL1 + ototalSRWRHD1_HD2TT

*OUTPUT ototalSRWRSPACEPARTIAL
*SOURCE ototalSRWRSPACEPARTIAL1 + ototalSRWRHD1_HD2ST

;__COST_TIME_SPACE for fully combined Roads, Water, and Sewer

*OUTPUT ototalRWSLD1_LD1A
*SOURCE ? ? ? ? ? ? ? ? ? ? ? ? ? ? ? ? ? ? ? ? ? ? aRWS_LD1_LD1 _AREA

*OUTPUT ototalRWSLD1_LD2A
*SOURCE ? ? ? ? ? ? ? ? ? ? ? ? ? ? ? ? ? ? ? ? ? ? aRWS_LD1_LD2 _AREA

*OUTPUT ototalRWSLD2_LD1A
*SOURCE ? ? ? ? ? ? ? ? ? ? ? ? ? ? ? ? ? ? ? ? ? ? aRWS_LD2_LD1 _AREA
```

*OUTPUT ototalRWSLD2_LD2A
*SOURCE ? aRWS_LD2_LD2 _AREA

*OUTPUT ototalRWSHD1_HD1A
*SOURCE ? aRWS_HD1_HD1 _AREA

*OUTPUT ototalRWSHD1_HD2A
*SOURCE ? aRWS_HD1_HD2 _AREA

*OUTPUT ototalRWSHD2_HD1A
*SOURCE ? aRWS_HD2_HD1 _AREA

*OUTPUT ototalRWSHD2_HD2A
*SOURCE ? aRWS_HD2_HD2 _AREA

*OUTPUT ototalRWSLD1_HD1A
*SOURCE ? aRWS_LD1_HD1 _AREA

*OUTPUT ototalRWSLD1_HD2A
*SOURCE ? aRWS_LD1_HD2 _AREA

*OUTPUT ototalRWSLD2_HD1A
*SOURCE ? aRWS_LD2_HD1 _AREA

*OUTPUT ototalRWSLD2_HD2A
*SOURCE ? aRWS_LD2_HD2 _AREA

*OUTPUT ototalRWSHD1_LD1A
*SOURCE ? aRWS_HD1_LD1 _AREA

*OUTPUT ototalRWSHD1_LD2A
*SOURCE ? aRWS_HD1_LD2 _AREA

*OUTPUT ototalRWSHD2_LD1A
*SOURCE ? aRWS_HD2_LD1 _AREA

*OUTPUT ototalRWSHD2_LD2A
*SOURCE ? aRWS_HD2_LD2 _AREA

*OUTPUT ototalRWS_LD1_LD1C
*SOURCE ? _INVENT yRWS-LD1-LD1$

*OUTPUT ototalRWS_LD1_LD2C
*SOURCE ? _INVENT yRWS-LD1-LD2$

*OUTPUT ototalRWS_LD1_HD1C
*SOURCE ? _INVENT yRWS-LD1-HD1$

*OUTPUT ototalRWS_LD1_HD2C
*SOURCE ? _INVENT yRWS-LD1-HD2$

*OUTPUT ototalRWS_LD2_LD1C
*SOURCE ? _INVENT yRWS-LD2-LD1$

*OUTPUT ototalRWS_LD2_LD2C
*SOURCE ? _INVENT yRWS-LD2-LD2$

*OUTPUT ototalRWS_LD2_HD1C
*SOURCE ? _INVENT yRWS-LD2-HD1$

*OUTPUT ototalRWS_LD2_HD2C
*SOURCE ? _INVENT yRWS-LD2-HD2$

*OUTPUT ototalRWS_HD1_LD1C
*SOURCE ? _INVENT yRWS-HD1-LD1$

*OUTPUT ototalRWS_HD1_LD2C
*SOURCE ? _INVENT yRWS-HD1-LD2$

*OUTPUT ototalRWS_HD1_HD1C
*SOURCE ? _INVENT yRWS-HD1-HD1$

*OUTPUT ototalRWS_HD1_HD2C
*SOURCE ? _INVENT yRWS-HD1-HD2$

*OUTPUT ototalRWS_HD2_LD1C
*SOURCE ? _INVENT yRWS-HD2-LD1$

*OUTPUT ototalRWS_HD2_LD2C
*SOURCE ? _INVENT yRWS-HD2-LD2$

*OUTPUT ototalRWS_HD2_HD1C
*SOURCE ? _INVENT yRWS-HD2-HD1$

*OUTPUT ototalRWS_HD2_HD2C
*SOURCE ? _INVENT yRWS-HD2-HD2$

*OUTPUT ototalRWS_LD1_LD1T
*SOURCE ? _INVENT yRWS-LD1-LD1L

*OUTPUT ototalRWS_LD1_LD2T

*SOURCE ? _INVENT yRWS-LD1-LD2L

*OUTPUT ototalRWS_LD1_HD1T
*SOURCE ? _INVENT yRWS-LD1-HD1L

*OUTPUT ototalRWS_LD1_HD2T
*SOURCE ? _INVENT yRWS-LD1-HD2L

*OUTPUT ototalRWS_LD2_LD1T
*SOURCE ? _INVENT yRWS-LD2-LD1L

*OUTPUT ototalRWS_LD2_LD2T
*SOURCE ? _INVENT yRWS-LD2-LD2L

*OUTPUT ototalRWS_LD2_HD1T
*SOURCE ? _INVENT yRWS-LD2-HD1L

*OUTPUT ototalRWS_LD2_HD2T
*SOURCE ? _INVENT yRWS-LD2-HD2L

*OUTPUT ototalRWS_HD1_LD1T
*SOURCE ? _INVENT yRWS-HD1-LD1L

*OUTPUT ototalRWS_HD1_LD2T
*SOURCE ? _INVENT yRWS-HD1-LD2L

*OUTPUT ototalRWS_HD1_HD1T
*SOURCE ? _INVENT yRWS-HD1-HD1L

*OUTPUT ototalRWS_HD1_HD2T
*SOURCE ? _INVENT yRWS-HD1-HD2L

*OUTPUT ototalRWS_HD2_LD1T
*SOURCE ? _INVENT yRWS-HD2-LD1L

*OUTPUT ototalRWS_HD2_LD2T
*SOURCE ? _INVENT yRWS-HD2-LD2L

*OUTPUT ototalRWS_HD2_HD1T
*SOURCE ? _INVENT yRWS-HD2-HD1L

*OUTPUT ototalRWS_HD2_HD2T
*SOURCE ? _INVENT yRWS-HD2-HD2L

*OUTPUT ototalRWS_LD1_LD1S
*SOURCE ? _INVENT yRWS-LD1-LD1!

*OUTPUT ototalRWS_LD1_LD2S
*SOURCE ? _INVENT yRWS-LD1-LD2!

*OUTPUT ototalRWS_LD1_HD1S
*SOURCE ? _INVENT yRWS-LD1-HD1!

*OUTPUT ototalRWS_LD1_HD2S
*SOURCE ? _INVENT yRWS-LD1-HD2!

*OUTPUT ototalRWS_LD2_LD1S
*SOURCE ? _INVENT yRWS-LD2-LD1!

*OUTPUT ototalRWS_LD2_LD2S
*SOURCE ? _INVENT yRWS-LD2-LD2!

*OUTPUT ototalRWS_LD2_HD1S
*SOURCE ? _INVENT yRWS-LD2-HD1!

*OUTPUT ototalRWS_LD2_HD2S
*SOURCE ? _INVENT yRWS-LD2-HD2!

*OUTPUT ototalRWS_HD1_LD1S
*SOURCE ? _INVENT yRWS-HD1-LD1!

*OUTPUT ototalRWS_HD1_LD2S
*SOURCE ? _INVENT yRWS-HD1-LD2!

*OUTPUT ototalRWS_HD1_HD1S
*SOURCE ? _INVENT yRWS-HD1-HD1!

*OUTPUT ototalRWS_HD1_HD2S
*SOURCE ? _INVENT yRWS-HD1-HD2!

*OUTPUT ototalRWS_HD2_LD1S
*SOURCE ? _INVENT yRWS-HD2-LD1!

*OUTPUT ototalRWS_HD2_LD2S
*SOURCE ? _INVENT yRWS-HD2-LD2!

*OUTPUT ototalRWS_HD2_HD1S
*SOURCE ? _INVENT yRWS-HD2-HD1!

*OUTPUT ototalRWS_HD2_HD2S
*SOURCE ? _INVENT yRWS-HD2-HD2!

*OUTPUT ototalRWSLD1_LD1CT
*SOURCE ototalRWSLD1_LD1A * ototalRWS_LD1_LD1C / 100000

*OUTPUT ototalRWSLD1_LD2CT
*SOURCE ototalRWSLD1_LD2A * ototalRWS_LD1_LD2C / 100000

*OUTPUT ototalRWSLD1_HD1CT
*SOURCE ototalRWSLD1_HD1A * ototalRWS_LD1_HD1C / 100000

*OUTPUT ototalRWSLD1_HD2CT
*SOURCE ototalRWSLD1_HD2A * ototalRWS_LD1_HD2C / 100000

*OUTPUT ototalRWSLD2_LD1CT
*SOURCE ototalRWSLD2_LD1A * ototalRWS_LD2_LD1C / 100000

*OUTPUT ototalRWSLD2_LD2CT
*SOURCE ototalRWSLD2_LD2A * ototalRWS_LD2_LD2C / 100000

*OUTPUT ototalRWSLD2_HD1CT
*SOURCE ototalRWSLD2_HD1A * ototalRWS_LD2_HD1C / 100000

*OUTPUT ototalRWSLD2_HD2CT
*SOURCE ototalRWSLD2_HD2A * ototalRWS_LD2_HD2C / 100000

*OUTPUT ototalRWSHD1_LD1CT
*SOURCE ototalRWSHD1_LD1A * ototalRWS_HD1_LD1C / 100000

*OUTPUT ototalRWSHD1_LD2CT
*SOURCE ototalRWSHD1_LD2A * ototalRWS_HD1_LD2C / 100000

*OUTPUT ototalRWSHD1_HD1CT
*SOURCE ototalRWSHD1_HD1A * ototalRWS_HD1_HD1C / 100000

*OUTPUT ototalRWSHD1_HD2CT
*SOURCE ototalRWSHD1_HD2A * ototalRWS_HD1_HD2C / 100000

*OUTPUT ototalRWSHD2_LD1CT
*SOURCE ototalRWSHD2_LD1A * ototalRWS_HD2_LD1C / 100000

*OUTPUT ototalRWSHD2_LD2CT
*SOURCE ototalRWSHD2_LD2A * ototalRWS_HD2_LD2C / 100000

*OUTPUT ototalRWSHD2_HD1CT
*SOURCE ototalRWSHD2_HD1A * ototalRWS_HD2_HD1C / 100000

*OUTPUT ototalRWSHD2_HD2CT

*SOURCE ototalRWSHD2_HD2A * ototalRWS_HD2_HD2C / 100000

*OUTPUT ototalRWSLD1_LD1TT
*SOURCE ototalRWSLD1_LD1A * ototalRWS_LD1_LD1T / 100000

*OUTPUT ototalRWSLD1_LD2TT
*SOURCE ototalRWSLD1_LD2A * ototalRWS_LD1_LD2T / 100000

*OUTPUT ototalRWSLD1_HD1TT
*SOURCE ototalRWSLD1_HD1A * ototalRWS_LD1_HD1T / 100000

*OUTPUT ototalRWSLD1_HD2TT
*SOURCE ototalRWSLD1_HD2A * ototalRWS_LD1_HD2T / 100000

*OUTPUT ototalRWSLD2_LD1TT
*SOURCE ototalRWSLD2_LD1A * ototalRWS_LD2_LD1T / 100000

*OUTPUT ototalRWSLD2_LD2TT
*SOURCE ototalRWSLD2_LD2A * ototalRWS_LD2_LD2T / 100000

*OUTPUT ototalRWSLD2_HD1TT
*SOURCE ototalRWSLD2_HD1A * ototalRWS_LD2_HD1T / 100000

*OUTPUT ototalRWSLD2_HD2TT
*SOURCE ototalRWSLD2_HD2A * ototalRWS_LD2_HD2T / 100000

*OUTPUT ototalRWSHD1_LD1TT
*SOURCE ototalRWSHD1_LD1A * ototalRWS_HD1_LD1T / 100000

*OUTPUT ototalRWSHD1_LD2TT
*SOURCE ototalRWSHD1_LD2A * ototalRWS_HD1_LD2T / 100000

*OUTPUT ototalRWSHD1_HD1TT
*SOURCE ototalRWSHD1_HD1A * ototalRWS_HD1_HD1T / 100000

*OUTPUT ototalRWSHD1_HD2TT
*SOURCE ototalRWSHD1_HD2A * ototalRWS_HD1_HD2T / 100000

*OUTPUT ototalRWSHD2_LD1TT
*SOURCE ototalRWSHD2_LD1A * ototalRWS_HD2_LD1T / 100000

*OUTPUT ototalRWSHD2_LD2TT
*SOURCE ototalRWSHD2_LD2A * ototalRWS_HD2_LD2T / 100000

*OUTPUT ototalRWSHD2_HD1TT
*SOURCE ototalRWSHD2_HD1A * ototalRWS_HD2_HD1T / 100000

*OUTPUT ototalRWSHD2_HD2TT
*SOURCE ototalRWSHD2_HD2A * ototalRWS_HD2_HD2T / 100000

*OUTPUT ototalRWSLD1_LD1ST
*SOURCE ototalRWSLD1_LD1A * ototalRWS_LD1_LD1S / 100000

*OUTPUT ototalRWSLD1_LD2ST
*SOURCE ototalRWSLD1_LD2A * ototalRWS_LD1_LD2S / 100000

*OUTPUT ototalRWSLD1_HD1ST
*SOURCE ototalRWSLD1_HD1A * ototalRWS_LD1_HD1S / 100000

*OUTPUT ototalRWSLD1_HD2ST
*SOURCE ototalRWSLD1_HD2A * ototalRWS_LD1_HD2S / 100000

*OUTPUT ototalRWSLD2_LD1ST
*SOURCE ototalRWSLD2_LD1A * ototalRWS_LD2_LD1S / 100000

*OUTPUT ototalRWSLD2_LD2ST
*SOURCE ototalRWSLD2_LD2A * ototalRWS_LD2_LD2S / 100000

*OUTPUT ototalRWSLD2_HD1ST
*SOURCE ototalRWSLD2_HD1A * ototalRWS_LD2_HD1S / 100000

*OUTPUT ototalRWSLD2_HD2ST
*SOURCE ototalRWSLD2_HD2A * ototalRWS_LD2_HD2S / 100000

*OUTPUT ototalRWSHD1_LD1ST
*SOURCE ototalRWSHD1_LD1A * ototalRWS_HD1_LD1S / 100000

*OUTPUT ototalRWSHD1_LD2ST
*SOURCE ototalRWSHD1_LD2A * ototalRWS_HD1_LD2S / 100000

*OUTPUT ototalRWSHD1_HD1ST
*SOURCE ototalRWSHD1_HD1A * ototalRWS_HD1_HD1S / 100000

*OUTPUT ototalRWSHD1_HD2ST
*SOURCE ototalRWSHD1_HD2A * ototalRWS_HD1_HD2S / 100000

*OUTPUT ototalRWSHD2_LD1ST
*SOURCE ototalRWSHD2_LD1A * ototalRWS_HD2_LD1S / 100000

*OUTPUT ototalRWSHD2_LD2ST
*SOURCE ototalRWSHD2_LD2A * ototalRWS_HD2_LD2S / 100000

*OUTPUT ototalRWSHD2_HD1ST
*SOURCE ototalRWSHD2_HD1A * ototalRWS_HD2_HD1S / 100000

*OUTPUT ototalRWSHD2_HD2ST
*SOURCE ototalRWSHD2_HD2A * ototalRWS_HD2_HD2S / 100000

*OUTPUT ototalRWSCOSTCOMBINED1
*SOURCE ototalRWSLD1_LD1CT + ototalRWSLD1_LD2CT + ototalRWSLD1_HD1CT + ototalRWSLD1_HD2CT + ototalRWSLD2_LD1CT + ototalRWSLD2_LD2CT + ototalRWSLD2_HD1CT + ototalRWSLD2_HD2CT + ototalRWSHD1_LD1CT + ototalRWSHD1_LD2CT + ototalRWSHD1_HD1CT

*OUTPUT ototalRWSTIMECOMBINED1
*SOURCE ototalRWSLD1_LD1TT + ototalRWSLD1_LD2TT + ototalRWSLD1_HD1TT + ototalRWSLD1_HD2TT + ototalRWSLD2_LD1TT + ototalRWSLD2_LD2TT + ototalRWSLD2_HD1TT + ototalRWSLD2_HD2TT + ototalRWSHD1_LD1TT + ototalRWSHD1_LD2TT + ototalRWSHD1_HD1TT

*OUTPUT ototalRWSSPACECOMBINED1
*SOURCE ototalRWSLD1_LD1ST + ototalRWSLD1_LD2ST + ototalRWSLD1_HD1ST + ototalRWSLD1_HD2ST + ototalRWSLD2_LD1ST + ototalRWSLD2_LD2ST + ototalRWSLD2_HD1ST + ototalRWSLD2_HD2ST + ototalRWSHD1_LD1ST + ototalRWSHD1_LD2ST + ototalRWSHD1_HD1ST

*OUTPUT ototalRWSCOSTCOMBINED
*SOURCE ototalRWSCOSTCOMBINED1 + ototalRWSHD1_HD2CT

*OUTPUT ototalRWSTIMECOMBINED
*SOURCE ototalRWSTIMECOMBINED1 + ototalRWSHD1_HD2TT

*OUTPUT ototalRWSSPACECOMBINED
*SOURCE ototalRWSSPACECOMBINED1 + ototalRWSHD1_HD2ST

;__ FINAL NETWORK OUTPUTS

*OUTPUT oCOSTTOTAL
*SOURCE ototalRWSCOSTCOMBINED + ototalRDSCOSTSILO

*OUTPUT oTIMETOTAL
*SOURCE ototalRWSTIMECOMBINED + ototalRDSTIMESILO

*OUTPUT oSPACETOTAL
*SOURCE ototalRWSSPACECOMBINED + ototalRDSSPACESILO

*OUTPUT oRISKTOTAL
*SOURCE oRSKCOR

```
*OUTPUT oCONDITIONTOTAL
*SOURCE oavrgRELCOR

*OUTPUT oRESILIENCETOTAL
*SOURCE oavrgcapSRWR
;###########################################################################################################################

;__ PENALTIES AND INCENTIVES

;*OUTPUT ototalPEN
;*SOURCE ? ? ? ? ? ? ? ? ? ? ? ? ? ? ? ? ? ? ? ? ? ? _INVENT yPEN

;*OUTPUT ototalINC
;*SOURCE ? ? ? ? ? ? ? ? ? ? ? ? ? ? ? ? ? ? ? ? ? ? _INVENT yINC

;*OUTPUT ototwm$spent_disc  Total spent discounted

; *SOURCE ototwm$spent * ydiscount

;    ****************condition states*************************

;*OUTPUT Vpoor_pvc(_TH1)
;*SOURCE pipes pvc2 ? ?  @YLD(ybci,0..17.99999999999) _INVENT _AREA

;*OUTPUT Vpoor_iron(_TH1)
;*SOURCE pipes iron ? ?  @YLD(ybci,0..17.99999999999) _INVENT _AREA

;*OUTPUT Vpoor_ac(_TH1)
;*SOURCE pipes concrete ? ?  @YLD(ybci,0..17.99999999999) _INVENT _AREA

;*OUTPUT Vpoor_steel(_TH1)
;*SOURCE pipes steel ? ?  @YLD(ybci,0..17.99999999999) _INVENT _AREA


;*OUTPUT Vpoor_pipes Length of very poor Pipes
;*SOURCE Vpoor_pvc + Vpoor_iron + Vpoor_ac + Vpoor_steel

;*OUTPUT oCONIDITONTOTAL
;* SOURCE OCONDITIONTOTAL >= 1.01 *  ototalcond[-1] 1.._LENGTH
```

8.5.8 *Optimize*

```
; Optimization Formulation
```

```
*OBJECTIVE

;--MULTI-OBJECTIVE MODEL

;--GOAL OPTIMIZAITON

_GOAL (G1,G2,G3,G4,G5,G6)

;--SINGLE OBJECTIVE MODE

    ;-- CONDITION-BASED OPTIMIZATION

;_MIN oCOSTTOTAL

     ;-- COST-BASED OPTIMIZATION

;_MAX oCONDITIONTOTAL _PENALTY(_ALL) 1..._LENGTH

*CONSTRAINTS
oCOSTTOTAL <= 10000000 1.._LENGTH _GOAL(G1,9999)
;_SEQ(oCOSTTOTAL, 0.1, 0.1) 1.._LENGTH
oTIMETOTAL <= 20000 1.._LENGTH _GOAL(G2,99)
oSPACETOTAL <= 600 1.._LENGTH _GOAL(G3,9)
oRISKTOTAL <= 3.5 1.._LENGTH _GOAL(G4,99)
oCONDITIONTOTAL >= 40 1.._LENGTH _GOAL(G5,9999999)
;_SEQ(oCONDITIONTOTAL, 10, 10) 1.._LENGTH
oRESILIENCETOTAL <= 80 1.._LENGTH _GOAL(G6,999)

*FORMAT MOSEK

 ;*OBJECTIVE
;_GOAL (G2,G3,G4,G5)
;_MAX ototalcond 1.. _LENGTH
;_MIN otot$expenditure 1.. _LENGTH

;*CONSTRAINTS

;otot$expenditure <= 1000000 1.._LENGTH _GOAL(G1,999)
;VeryPoor_capacity1 <= 0 1.._LENGTH _GOAL(G2,99999)
;VeryPoor_capacity2 <= 0 1.._LENGTH _GOAL(G3,9999)
;VeryPoor_capacity3 <= 0 1.._LENGTH _GOAL(G4,99999)
;ototalcond >= 278840  1.._LENGTH _GOAL(G5,999)
;oreplacesameall >= 10 1.._LENGTH _GOAL(G6,9999999999999999)
;VeryPoor_condition <= 0 1.._LENGTH _GOAL(G5,999)
```

```
;ototalcond >= 1.01 *  ototalcond[-1] 1.._LENGTH    ==> Greater than 1% of the previous year
_GOAL(G1,9999)

;ototalVIR >= ototalVIR[-1] 1.._LENGTH
;otot$expenditure >= 100000 1.._LENGTH
;otot$Spend <= 110000 11.._LENGTH
;_SEQ(otot$Spend, 0.01, 0.01) 1.._LENGTH     ==> Soft constraint for output up and down
_GOAL(G2,9999)
;Good_roads >= good_roads[-1] 1.._LENGTH
;Fair_roads >= fair_roads[-1] 1.._LENGTH
;Killroads <= killroads[-1] 1.._LENGTH

;ototcapleft <= 418260 1.._LENGTH
;_NDY(ototcapleft) 1.._LENGTH         ==> _GOAL(G3,9999);Non declining yeild to ensure
variable is not declining (Softer)
```

8.5.9 *Graphics*

```
*PAGE GRAPHICS Section
*SCREENSIZE MAXIMIZED
*FONT1 "Tahoma" 12 0 1000
*FONT2 "Tahoma" 8 0 0000
*FONT3 "Tahoma" 8 0 0000
*YEARS 2017 1
*WINDOW {1}(1,721,361,968) "Network Costs" _BAR
 _LEGEND (226,738)
_YAXIS(*,*,*,6)
*WINDOW {2}(1,350,508,721) "Network Repair Time" _BAR
 _LEGEND (54,372)
_YAXIS(*,*,*,6)
*WINDOW {3}(508,350,993,721) "Network Repair Space" _BAR
 _LEGEND (567,366)
_YAXIS(*,*,*,6)
*WINDOW {4}(1,1,338,350) "Network Reliability"
 _LEGEND (262,223)
_YAXIS(*,*,*,6)
*WINDOW {5}(338,1,688,350) "Network Risk"
 _LEGEND (627,32)
_YAXIS(*,*,*,6)
*WINDOW {6}(361,721,632,968) "Network full coordination" _BAR
 _LEGEND (407,748)
_YAXIS(*,*,*,6)
*WINDOW {7}(632,721,993,968) "Network conventional actions" _BAR
 _LEGEND (701,753)
_YAXIS(*,*,*,6)
*WINDOW {8}(688,1,993,350) "Network Resilience Preparedness"
```

```
  _LEGEND (920,25)
_YAXIS(*,*,*,6)
*LINES
  OCOSTTOTAL 1 1 _MAROON _SOLID "Ocosttotal "
  OTIMETOTAL 2 1 _GRAY _SOLID "Otimetotal "
  OTOTALRDSTIMESILO 2 1 _NAVY _SOLID "Ototalrdstimesilo "
  OTOTALRWSTIMECOMBINED 2 1 _EMERALD _SOLID "Ototalrwstimecombined "
  OSPACETOTAL 3 1 _EMERALD _SOLID "Ospacetotal "
  OTOTALRWSSPACECOMBINED 3 1 _MUSTARD _SOLID "Ototalrwsspacecombined "
  OTOTALRDSSPACESILO 3 1 _PURPLE _SOLID "Ototalrdsspacesilo "
  OCONDITIONTOTAL 4 1 _MAROON _TRIANGLE _SOLID "Oconditiontotal "
  OAVRGPCIRD 4 1 _PINK _NONE _SOLID "Oavrgpcird "
  OAVRGRELWR 4 1 _BLUE _CROSS _SOLID "Oavrgrelwr "
  OAVRGRELSR 4 1 _MUSTARD _TRIANGLE _SOLID "Oavrgrelsr "
  ORSKWRD 5 1 _SCARLET _NONE _SOLID "Orskwrd "
  ORSKWSR 5 1 _GRAY _SQUARE _SOLID "Orskwsr "
  ORSKWWR 5 1 _PURPLE _NONE _SOLID "Orskwwr "
  ORISKTOTAL 5 1 _EMERALD _NONE _SOLID "Orisktotal "
  OTOTALRWSCOSTCOMBINED 6 1 _EMERALD _SOLID "Ototalrwscostcombined "
  OTOTALRDSCOSTSILO 7 1 _EMERALD _SOLID "Ototalrdscostsilo "
  ORESILIENCETOTAL 8 1 _BLUE _SQUARE _SOLID "Oresiliencetotal "
  OAVRGCAPSR 8 1 _PINK _CROSS _SOLID "Oavrgcapsr "
  OAVRGCAPWR 8 1 _MUSTARD _CIRCLE _SOLID "Oavrgcapwr "
*PAGE
*PAGE
```

8.5.10 *Schedule*

```
; File created on Nov 21 2018 at 8:23:40 pm
; Interpreter (Wk32.exe) version      7.4.0
; Editor version (Wke32.exe)          7.4.0
; Lp Report writer (Lp2wk.exe) version 7.4.0
; Elapsed time for solver 00:00:22

; Mosek reported :
;
;SOLUTION STATUS     : OPTIMAL
;OBJECTIVE NAME      : OBJ1MIN
;PRIMAL OBJECTIVE    : 1.88539860e+14
;DUAL OBJECTIVE      : 1.88539860e+14
;
{ _Goal Summary begins
Constraint: OPCIRD - 1.1 * OPCIRD[-1] >= 0 1.._LENGTH _GOAL(G3,9999999)
   Period        Above        Below
      1          0.00     519,810.50
```

2	0.00	514,459.50
3	0.00	488,125.09
4	0.00	479,678.59
5	0.00	476,455.81
6	0.00	469,773.00
7	0.00	459,789.09
8	0.00	476,494.69
9	0.00	462,371.00
10	0.00	475,269.59
11	0.00	461,914.69
12	0.00	442,942.41
13	0.00	450,549.69
14	0.00	440,556.50

Constraint: ORELSR - 1.1 * ORELSR[-1] >= 0 1.._LENGTH _GOAL(G1,9999999)

Period	Above	Below
1	0.00	518,704.50
2	0.00	511,626.00
3	0.00	511,624.81
4	0.00	498,175.59
5	0.00	493,426.81
6	0.00	494,718.81
7	0.00	480,749.81
8	0.00	478,274.19
9	0.00	457,021.41
10	0.00	453,015.81
11	0.00	447,241.69
12	0.00	424,208.91
13	0.00	421,586.69
14	0.00	404,837.63
15	0.00	259,103.72
16	0.00	219,413.34
17	0.00	183,884.67
18	0.00	100,849.45
19	0.00	88,384.33
20	0.00	100,951.85

Constraint: ORELWR - 1.1 * ORELWR[-1] >= 0 1.._LENGTH _GOAL(G2,9999999)

Period	Above	Below
1	0.00	252,737.25
2	0.00	252,542.30
3	0.00	215,350.00
4	0.00	258,814.91
5	0.00	258,078.09
6	0.00	257,730.91
7	0.00	258,218.20
8	0.00	258,585.20
9	0.00	259,145.30

10	0.00	258,675.70
11	0.00	261,630.59
12	0.00	255,146.09
13	0.00	254,070.00
14	0.00	252,308.41
15	0.00	250,224.00
16	0.00	216,251.39
17	0.00	217,939.66
18	0.00	232,774.94
19	0.00	217,774.73

_Goal Summary ends {}
;SCHEDULE begins
;Th1 Th2 Th3 Th4 Th5 Th6 Th7 Th8 Th9 Th10 Th11 Th12 Th13 Th14 Th15 Th16 Th17 Th18 Th19 Th20 Th21 Age Area Action Period Condition
ROAD WEAK LIGHT NONE SANITARY PVC S8 NO WM PVC S6 NON -60 -4 15 17 45 HIGH MEDIUM -40 -1 18 441.000000 ARS 12 _EXISTING ;A3026 100.0% of class
GRAVEL WEAK LIGHT NONE SANITARY AC S8 NO WM PVC S6 NON -36 -22 15 17 244 HIGH MEDIUM -16 -17 31 23.874207 ARWS_HD2_LD2 14 _EXISTING ;A6960 6.0% of class
GRAVEL WEAK LIGHT NONE SANITARY PVC S8 NO WM PVC S6 NON -22 -45 15 17 21 LOW HIGH -2 -40 32 86.223682 ARC 15 _EXISTING ;A8290 5.4% of class
ROAD WEAK LIGHT NONE SANITARY AC S8 NO WM PVC S8 NON -46 0 15 17 13 HIGH LOW -26 -5 15 241.000000 ARS 15 _EXISTING ;A7747 100.0% of class
ROAD WEAK LIGHT NONE STORM PVC S12 NO WM PVC S8 NON -30 -6 15 17 68 HIGH LOW -10 -1 21 381.000000 ARWS_HD2_LD1 15 _EXISTING ;A9167 100.0% of class
ROAD WEAK LIGHT NONE STORM PVC S12 NO WM PVC S8 NON -30 -6 15 17 70 HIGH MEDIUM -10 -1 17 376.000000 ARWS_HD2_LD1 15 _EXISTING ;A9166 100.0% of class
GRAVEL WEAK LIGHT NONE SANITARY AC S8 NO WM PVC S6 NON -36 -22 15 17 244 HIGH MEDIUM -16 -17 32 375.125793 ARWS_HD2_LD2 15 _EXISTING ;A9377 94.0% of class
GRAVEL WEAK LIGHT NONE SANITARY PVC S8 NO WM PVC S6 NON -22 -22 15 17 20 HIGH LOW -17 -17 32 717.000000 ARWS_HD2_LD2 15 _EXISTING ;A9375 100.0% of class
GRAVEL WEAK LIGHT NONE SANITARY PVC S8 NO WM PVC S6 NON -22 -45 15 17 21 LOW HIGH -2 -40 32 1503.776318 ARWS_LD2_HD2 15 _EXISTING ;A9022 94.6% of class
ROAD STRONG LIGHT NONE STORM AC S8 NO WM PVC S8 NON -38 -24 15 17 47 LOW HIGH -18 -19 21 1339.000000 ARWS_LD2_HD2 15 _EXISTING ;A9018 100.0% of class
ROAD WEAK LIGHT NONE STORM CONC S24 NO WM PVC S8 NON -54 -11 15 17 86 MEDIUM HIGH -34 -6 25 151.075176 ARWS_LD2_HD2 15 _EXISTING ;A9000 63.5% of class
GRAVEL WEAK LIGHT NONE SANITARY PVC S8 NO WM PVC S6 NON -16 -22 15 17 33 LOW MEDIUM -4 -17 32 429.000000 ARWS_LD2_LD2 15 _EXISTING ;A8619 100.0% of class
ROAD WEAK LIGHT NONE SANITARY VCT S8 NO WM AC S8 NON -70 -35 15 17 206 MEDIUM MEDIUM -50 -30 18 376.000000 ARS 16 _EXISTING ;A10272 100.0% of class

ROAD WEAK LIGHT NONE STORM AC S8 NO WM PVC S8 NON -56 -6 15 17 190 HIGH LOW -36 -1 16 147.000000 ARS 16 _EXISTING ;A10271 100.0% of class
ROAD WEAK LIGHT NONE STORM CONC S15 NO WM PVC S8 NON -54 -15 15 17 117 MEDIUM MEDIUM -34 -10 16 240.000000 ARS 16 _EXISTING ;A10268 100.0% of class
ROAD WEAK LIGHT NONE STORM CONC S15 NO WM PVC S8 NON -54 -15 15 17 118 HIGH MEDIUM -34 -10 18 236.000000 ARS 16 _EXISTING ;A10267 100.0% of class
ROAD WEAK LIGHT NONE STORM CONC S15 NO WM STEEL S8 NON -54 -46 15 17 135 MEDIUM HIGH -34 -41 16 381.000000 ARS 16 _EXISTING ;A10266 100.0% of class
ROAD WEAK LIGHT NONE STORM CONC S18 NO WM CI S8 NON -54 -52 15 17 83 HIGH MEDIUM -34 -47 18 380.000000 ARS 16 _EXISTING ;A10265 100.0% of class
ROAD WEAK LIGHT NONE STORM CONC S18 NO WM PVC S6 NON -54 -11 15 17 88 HIGH LOW -34 -6 18 376.000000 ARS 16 _EXISTING ;A10264 100.0% of class
ROAD WEAK LIGHT NONE STORM CONC S18 NO WM PVC S8 NON -56 -17 15 17 107 MEDIUM HIGH -36 -12 16 380.000000 ARS 16 _EXISTING ;A10263 100.0% of class
ROAD WEAK LIGHT NONE STORM CONC S18 NO WM UCI S6 NON -56 -42 15 17 106 LOW HIGH -36 -37 18 236.000000 ARS 16 _EXISTING ;A10262 100.0% of class
ROAD WEAK LIGHT NONE STORM CONC S21 NO WM PVC S8 NON -56 -17 15 17 110 MEDIUM LOW -36 -12 16 380.000000 ARS 16 _EXISTING ;A10261 100.0% of class
ROAD WEAK LIGHT NONE STORM CONC S24 NO WM PVC S8 NON -56 -21 15 17 103 HIGH MEDIUM -36 -16 16 381.000000 ARS 16 _EXISTING ;A10260 100.0% of class
ROAD WEAK LIGHT NONE STORM PVC S12 NO WM UCI S6 NON -30 -55 15 17 69 LOW HIGH -10 -50 18 236.000000 ARS 16 _EXISTING ;A10258 100.0% of class
ROAD WEAK LIGHT NONE STORM VCT S12 NO WM CI S6 NON -54 -45 15 17 147 LOW HIGH -34 -40 18 380.000000 ARS 16 _EXISTING ;A10256 100.0% of class
ROAD WEAK LIGHT RS SANITARY PVC S8 NO WM PVC S6 NON -60 -4 15 17 45 HIGH MEDIUM -40 -1 15 88.200000 ARS 16 _FUTURE ;R9401
ROAD WEAK LIGHT NONE STORM CONC S21 NO WM PVC S8 NON -56 -22 15 17 109 HIGH LOW -36 -17 22 380.000000 ARWS_HD2_LD1 16 _EXISTING ;A12092 100.0% of class
ROAD STRONG MEDIUM NONE SANITARY PVC S10 NO WM AC S8 NON -12 -29 15 17 5 HIGH MEDIUM -8 -24 22 656.000000 ARWS_HD2_LD2 16 _EXISTING ;A12342 100.0% of class
ROAD WEAK LIGHT NONE STORM CONC S21 NO WM PVC S8 NON -56 -15 15 17 112 HIGH MEDIUM -36 -10 24 376.000000 ARWS_HD2_LD2 16 _EXISTING ;A12331 100.0% of class
ROAD WEAK LIGHT NONE STORM CONC S21 NO WM PVC S8 NON -56 -21 15 17 111 HIGH MEDIUM -36 -16 22 240.000000 ARWS_HD2_LD2 16 _EXISTING ;A12330 100.0% of class
ROAD WEAK LIGHT NONE SANITARY PVC S8 NO WM CI S6 NON -11 4 15 17 46 MEDIUM HIGH -9 -9 16 15.315268 ARWS_LD2_HD2 16 _EXISTING ;A11896 4.1% of class
ROAD WEAK LIGHT NONE STORM CONC S21 NO WM PVC S8 NON -56 -21 15 17 104 MEDIUM HIGH -36 -16 22 381.000000 ARWS_LD2_HD2 16 _EXISTING ;A11881 100.0% of class
ROAD WEAK LIGHT NONE STORM CONC S24 NO WM PVC S8 NON -54 -11 15 17 86 MEDIUM HIGH -34 -6 26 86.924824 ARWS_LD2_HD2 16 _EXISTING ;A11880 36.5% of class

ROAD STRONG LIGHT NONE STORM VCT S18 NO WM PVC S6 NON -35 3 15 17 171 MEDIUM LOW -15 -8 22 899.000000 ARWS_LD2_LD1 16 _EXISTING ;A11234 100.0% of class
ROAD WEAK LIGHT NONE STORM CONC S21 NO WM PVC S6 NON -56 -22 15 17 108 MEDIUM LOW -36 -17 22 241.000000 ARWS_LD2_LD1 16 _EXISTING ;A11232 100.0% of class
ROAD WEAK LIGHT NONE STORM CONC S30 NO WM PVC S8 NON -56 -11 15 17 102 MEDIUM MEDIUM -36 -6 22 238.000000 ARWS_LD2_LD2 16 _EXISTING ;A11398 100.0% of class
ROAD WEAK LIGHT NONE STORM VCT S12 NO WM PVC S8 NON -54 -4 15 17 142 HIGH LOW -34 -1 23 376.000000 ARWS_HD2_LD1 17 _EXISTING ;A15607 100.0% of class
ROAD STRONG LIGHT NONE SANITARY PVC S8 NO WM AC S6 NON -17 -31 15 17 40 HIGH MEDIUM -3 -26 21 562.000000 ARWS_HD2_LD2 17 _EXISTING ;A15919 100.0% of class
GRAVEL WEAK LIGHT NONE SANITARY CONC S8 NO WM PVC S6 NON -45 -3 15 17 258 MEDIUM HIGH -25 -2 34 537.954527 ARWS_LD2_HD2 17 _EXISTING ;A15374 74.0% of class
ROAD STRONG LIGHT NONE STORM PVC S18 NO WM AC S6 NON -35 -26 15 17 52 MEDIUM HIGH -15 -21 29 738.000000 ARWS_LD2_HD2 17 _EXISTING ;A15364 100.0% of class
ROAD WEAK LIGHT NONE STORM CONC S21 NO WM AC S6 NON -54 -31 15 17 76 LOW HIGH -34 -26 25 236.000000 ARWS_LD2_HD2 17 _EXISTING ;A15345 100.0% of class
ROAD WEAK LIGHT NONE STORM VCT S12 NO WM PVC S6 NON -54 -4 15 17 143 MEDIUM HIGH -34 -1 23 236.000000 ARWS_LD2_HD2 17 _EXISTING ;A15335 100.0% of class
GRAVEL WEAK LIGHT NONE SANITARY VCT S8 NO WM PVC S6 NON -45 -22 15 17 259 LOW MEDIUM -25 -17 34 393.000000 ARWS_LD2_LD2 17 _EXISTING ;A14769 100.0% of class
ROAD STRONG LIGHT NONE STORM PVC S18 NO WM PVC S6 NON -35 -24 15 17 177 MEDIUM MEDIUM -15 -19 23 649.000000 ARWS_LD2_LD2 17 _EXISTING ;A14767 100.0% of class
ROAD STRONG LIGHT NONE STORM PVC S18 NO WM PVC S8 NON -35 -24 15 17 176 LOW MEDIUM -15 -19 23 1215.000000 ARWS_LD2_LD2 17 _EXISTING ;A14766 100.0% of class
ROAD WEAK LIGHT NONE STORM VCT S12 NO WM PVC S6 NON -54 -4 15 17 150 MEDIUM MEDIUM -34 -1 23 230.000000 ARWS_LD2_LD2 17 _EXISTING ;A14749 100.0% of class
ROAD STRONG LIGHT NONE STORM VCT S12 NO WM PVC S6 NON -54 -45 15 17 75 HIGH LOW -34 -40 30 258.686190 ARWS_HD2_LD2 18 _EXISTING ;A20149 57.7% of class
ROAD WEAK LIGHT NONE STORM CONC S12 NO WM PVC S8 NON -56 -6 15 17 138 HIGH MEDIUM -36 -1 24 381.000000 ARWS_HD2_LD2 18 _EXISTING ;A20144 100.0% of class
ROAD WEAK LIGHT NONE STORM CONC S15 NO WM PVC S8 NON -55 -4 15 17 140 HIGH MEDIUM -35 -1 24 376.000000 ARWS_HD2_LD2 18 _EXISTING ;A20139 100.0% of class

GRAVEL WEAK LIGHT NONE SANITARY CONC S8 NO WM PVC S6 NON -45 -3 15 17 258 MEDIUM HIGH -25 -2 35 189.045473 ARWS_LD2_HD2 18 _EXISTING ;A19497 26.0% of class
ROAD STRONG HIGH NONE STORM CONC S8 NO WM PVC S16 NON -54 -21 15 17 199 MEDIUM HIGH -34 -16 26 1648.000000 ARWS_LD2_HD2 18 _EXISTING ;A19491 100.0% of class
ROAD STRONG MEDIUM NONE STORM CONC S30 NO WM PVC S8 NON -56 -17 15 17 101 LOW HIGH -36 -12 22 238.000000 ARWS_LD2_HD2 18 _EXISTING ;A19484 100.0% of class
ROAD WEAK LIGHT NONE STORM CONC S18 NO WM PVC S12 NON -55 -15 15 17 116 MEDIUM HIGH -35 -10 24 376.000000 ARWS_LD2_HD2 18 _EXISTING ;A19473 100.0% of class
ROAD WEAK LIGHT NONE STORM CONC S18 NO WM PVC S6 NON -55 -4 15 17 115 LOW HIGH -35 -1 26 265.000000 ARWS_LD2_HD2 18 _EXISTING ;A19472 100.0% of class
ROAD WEAK LIGHT NONE STORM CONC S15 NO WM PVC S8 NON -56 -21 15 17 137 MEDIUM LOW -36 -16 24 381.000000 ARWS_LD2_LD1 18 _EXISTING ;A18539 100.0% of class
ROAD WEAK LIGHT NONE SANITARY PVC S8 NO WM CI S6 NON -11 4 15 17 46 MEDIUM HIGH -9 -9 19 360.684732 ARC 19 _EXISTING ;A22817 95.9% of class
ROAD STRONG LIGHT NONE STORM PVC S18 NO WM PVC S8 NON -35 -20 15 17 179 HIGH LOW -15 -15 21 225.000000 ARWS_HD2_LD1 19 _EXISTING ;A24698 100.0% of class
ROAD WEAK LIGHT NONE STORM CONC S12 NO WM PVC S8 NON -56 -6 15 17 139 HIGH LOW -36 -1 31 381.000000 ARWS_HD2_LD1 19 _EXISTING ;A24694 100.0% of class
ROAD STRONG LIGHT NONE STORM VCT S12 NO WM PVC S6 NON -54 -45 15 17 75 HIGH LOW -34 -40 31 189.313810 ARWS_HD2_LD2 19 _EXISTING ;A25120 42.3% of class
ROAD WEAK LIGHT NONE SANITARY CONC S8 NO WM PVC S6 NON -60 -45 15 17 221 HIGH LOW -40 -40 36 294.297316 ARWS_HD2_LD2 19 _EXISTING ;A25117 43.5% of class
ROAD WEAK LIGHT NONE STORM CONC S15 NO WM UCI S6 NON -54 -42 15 17 95 HIGH MEDIUM -34 -37 25 376.000000 ARWS_HD2_LD2 19 _EXISTING ;A25109 100.0% of class
ROAD WEAK LIGHT NONE STORM PVC S10 NO WM PVC S6 NON -30 -24 15 17 64 HIGH LOW -10 -19 36 473.000000 ARWS_HD2_LD2 19 _EXISTING ;A25102 100.0% of class
ROAD WEAK LIGHT NONE STORM VCT S12 NO WM CI S8 NON -54 -46 15 17 148 HIGH LOW -34 -41 25 236.000000 ARWS_HD2_LD2 19 _EXISTING ;A25097 100.0% of class
ROAD WEAK LIGHT NONE STORM VCT S12 NO WM CI S6 NON -54 -47 15 17 125 MEDIUM HIGH -34 -42 25 236.000000 ARWS_LD2_HD2 19 _EXISTING ;A24305 100.0% of class
ROAD STRONG HIGH NONE STORM CONC S18 NO WM PVC S8 NON -56 -23 15 17 167 MEDIUM LOW -36 -18 27 693.000000 ARWS_LD2_LD1 19 _EXISTING ;A23224 100.0% of class

ROAD WEAK LIGHT NONE STORM CONC S15 NO WM CI S6 NON -54 -45 15 17 91 LOW MEDIUM -34 -40 25 236.000000 ARWS_LD2_LD2 19 _EXISTING ;A23500 100.0% of class
ROAD WEAK LIGHT NONE STORM CONC S8 NO WM CI S6 NON -54 -45 15 17 197 MEDIUM MEDIUM -34 -40 27 380.000000 ARWS_LD2_LD2 19 _EXISTING ;A23493 100.0% of class
ROAD WEAK LIGHT NONE STORM VCT S10 NO WM AC S6 NON -54 -41 15 17 154 LOW MEDIUM -34 -36 19 4.441272 ARWS_LD2_LD2 19 _EXISTING ;A23492 2.4% of class
ROAD STRONG MEDIUM NONE STORM AC S8 NO WM PVC S8 NON -56 -17 15 17 186 HIGH LOW -36 -12 24 236.000000 ARWS_HD2_LD1 20 _EXISTING ;A30383 100.0% of class
ROAD WEAK LIGHT RS SANITARY AC S8 NO WM PVC S8 NON -46 0 15 17 13 HIGH LOW -26 -5 16 48.200000 ARWS_HD2_LD1 20 _FUTURE ;R29967
ROAD STRONG HIGH NONE STORM CONC S24 NO WM CI S6 NON -54 -52 15 17 81 HIGH LOW -34 -47 22 237.000000 ARWS_HD2_LD2 20 _EXISTING ;A30874 100.0% of class
ROAD WEAK LIGHT NONE STORM CONC S15 NO WM CI S6 NON -54 -52 15 17 127 HIGH MEDIUM -34 -47 26 236.000000 ARWS_HD2_LD2 20 _EXISTING ;A30863 100.0% of class
ROAD WEAK LIGHT NONE STORM CONC S18 NO WM AC S6 NON -54 -39 15 17 77 HIGH MEDIUM -34 -34 28 208.704568 ARWS_HD2_LD2 20 _EXISTING ;A30859 88.4% of class
ROAD WEAK LIGHT NONE STORM CONC S18 NO WM AC S6 NON -54 -39 15 17 84 HIGH LOW -34 -34 26 372.000000 ARWS_HD2_LD2 20 _EXISTING ;A30858 100.0% of class
ROAD STRONG MEDIUM NONE STORM CONC S8 NO WM PVC S8 NON -56 -17 15 17 185 MEDIUM HIGH -36 -12 24 212.589320 ARWS_LD2_HD2 20 _EXISTING ;A29950 88.6% of class
ROAD WEAK LIGHT NONE STORM CONC S15 NO WM CI S8 NON -54 -52 15 17 90 MEDIUM HIGH -34 -47 26 380.000000 ARWS_LD2_HD2 20 _EXISTING ;A29943 100.0% of class
ROAD WEAK LIGHT NONE STORM CONC S21 NO WM CI S6 NON -56 -55 15 17 113 LOW HIGH -36 -50 26 236.000000 ARWS_LD2_HD2 20 _EXISTING ;A29934 100.0% of class
ROAD WEAK LIGHT NONE STORM VCT S12 NO WM CI S6 NON -54 -53 15 17 131 MEDIUM HIGH -34 -48 22 376.000000 ARWS_LD2_HD2 20 _EXISTING ;A29926 100.0% of class
GRAVEL WEAK LIGHT NONE SANITARY PVC S8 NO WM AC S6 NON -16 -32 15 17 32 LOW MEDIUM -4 -27 37 24.861576 ARWS_LD2_LD2 20 _EXISTING ;A29007 4.6% of class
ROAD STRONG HIGH NONE STORM CONC S8 NO WM AC S6 NON -54 -40 15 17 159 MEDIUM MEDIUM -34 -35 28 1012.000000 ARWS_LD2_LD2 20 _EXISTING ;A29002 100.0% of class
ROAD WEAK LIGHT NONE STORM CONC S15 NO WM CI S6 NON -56 -53 15 17 133 MEDIUM MEDIUM -36 -48 22 380.000000 ARWS_LD2_LD2 20 _EXISTING ;A28993 100.0% of class

ROAD WEAK LIGHT NONE STORM CONC S15 NO WM CI S6 NON -56 -53 15 17 134 LOW MEDIUM -36 -48 22 236.000000 ARWS_LD2_LD2 20 _EXISTING ;A28992 100.0% of class
ROAD WEAK LIGHT NONE STORM VCT S10 NO WM AC S6 NON -54 -41 15 17 154 LOW MEDIUM -34 -36 20 182.558728 ARWS_LD2_LD2 20 _EXISTING ;A28986 97.6% of class
ROAD WEAK LIGHT NONE STORM PVC S8 NO WM PVC S6 NON -50 -24 15 17 27 HIGH LOW -30 -19 38 651.726123 ARWS_HD2_LD2 21 _EXISTING ;A37503 88.2% of class
ROAD WEAK LIGHT RS STORM CONC S18 NO WM CI S8 NON -54 -52 15 17 83 HIGH MEDIUM -34 -47 16 76.000000 ARWS_HD2_LD2 21 _FUTURE ;R36982
ROAD WEAK LIGHT RS STORM CONC S24 NO WM PVC S8 NON -56 -21 15 17 103 HIGH MEDIUM -36 -16 16 76.200000 ARWS_HD2_LD2 21 _FUTURE ;R36970
ROAD STRONG LIGHT NONE STORM CONC S15 NO WM CI S8 NON -54 -50 15 17 128 LOW HIGH -34 -45 21 223.820744 ARWS_LD2_HD2 21 _EXISTING ;A36464 58.9% of class
ROAD STRONG LIGHT NONE STORM PVC S8 NO WM AC S6 NON -45 -30 15 17 61 LOW HIGH -25 -25 29 824.000000